AD NUMBER
ADB183172

NEW LIMITATION CHANGE

TO

Approved for public release, distribution unlimited

FROM

Distribution authorized to U.S. Gov't. agencies and their contractors; Administrative/Operational Use; 04 MAY 1954. Other requests shall be referred to National Aeronautics and Space Administration, Washington, DC 20546.

AUTHORITY

NASA TR Server Website
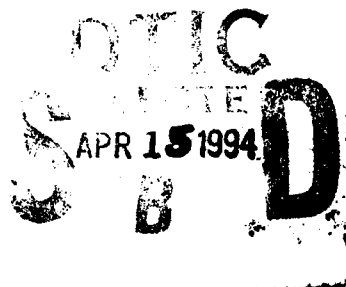
AD-B183 172

THE DESIGN OF LARGE HIGH-SPEED WIND TUNNELS

by

Ralph F. Huntsberger and John F. Parsons

National Advisory Committee for Aeronautics
Ames Aeronautical Laboratory
Moffett Field, Calif.

Paper to be presented for round-table

discussion of design problems of

large high-speed wind tunnels

AGARD

Fourth General Assembly

Wind-Tunnel Panel

May 4, 1954

Scheveningen

Netherlands

THE DESIGN OF LARGE HIGH-SPEED WIND TUNNELS

by

Ralph F. Huntsberger[1] and John F. Parsons[2]

National Advisory Committee for Aeronautics
Ames Aeronautical Laboratory
Moffett Field, Calif.

The rapid development of aircraft in the past several decades is a reflection of the concurrent improvement of the aeronautical research equipment which made that development possible. The variety of the research information needed and the rapidity with which it has been required has continually increased the complexity of the research equipment and taxed the ingenuity of the engineering personnel responsible for the design and construction of the facilities. Experience, in the United States, has shown that the complexity of aeronautical research equipment becomes increasingly greater as the design speed is raised.

One of the aspects of this general development has been the requirement for large high-speed wind tunnels capable of producing reliable data at Reynolds numbers approaching those of actual flight. The design and construction of this type of facility poses many problems not usually encountered in ordinary engineering work, and, because of the relative paucity of such facilities, these problems and their solutions may remain undisclosed except to those persons directly concerned with a particular design. While it is recognized that varying conditions may predicate different solutions for many of the problems encountered, it is believed that some assistance in future designs might be gained from the experience encountered in the United States by the National Advisory Committee for Aeronautics.

In order to reasonably restrict the scope of a paper recounting NACA experience in the design of large high-speed wind tunnels, the terms "large" and "high speed" must be defined. Since 1945 the NACA has designed and placed into operation several large transonic and supersonic wind tunnels and at present is engaged in the design and construction of even larger and higher speed facilities. For the purpose of this paper, the specifications of these newer facilities will form the basis for the rather arbitrary definitions of "large" and "high speed." It is realized that many of the design considerations to be discussed may well apply to wind tunnels falling outside the limits of these definitions. However, in order to emphasize the problems of the large wind tunnel, consideration will be limited to those larger wind tunnels described below in

---

[1]Head, Unitary Plan Design Group.
[2]Associate Director, Ames Aeronautical Laboratory and Chief, Project Office, Unitary Wind-Tunnel Program, NACA.

which the most recent design experience has been obtained. In addition, a high-speed wind tunnel will be considered as one capable of operation through the transonic speed range or at higher speeds up to a Mach number of 4.0.

The upper limit of the speed range was selected because above that Mach number, special problems, such as liquefaction of the air stream at normal operating temperatures, would be introduced. Other special problems introduced by intermittent operation, operation at low densities, and the scavenging of exhaust gases in a propulsion wind tunnel are also considered to be outside the scope of this paper. Accordingly, consideration will be given principally to wind tunnels capable of operating at normal atmospheric stagnation densities or higher; to propulsion wind tunnels with atmospheric intake and discharge; and to aerodynamic wind tunnels with continuous-flow passages, and capable of density variation and humidity control. Finally, consideration will be given only to those wind tunnels capable of continuous Mach number variation, since, in general, it will be found uneconomical to build high-speed wind tunnels in large sizes with fixed Mach number nozzles. When the foregoing specifications are stipulated for large high-speed wind tunnels, it becomes evident that operating power requirements of 100,000 horsepower, or more, will be experienced.

The design experience presented herein has been largely gained through association with the design, construction, and operation of facilities which generally conform to the category just defined. These wind tunnels are described briefly hereinafter:

(1) The 8- by 6-foot supersonic propulsion wind tunnel located at the Lewis Flight Propulsion Laboratory, Cleveland, Ohio. This wind tunnel, with atmospheric intake and discharge, operates over a Mach number range from 1.4 to 2.0, the speed variation being accomplished by a pair of flexible walls in the nozzle. The drive is rated at 90,000 horsepower.

(2) The 6- by 6-foot supersonic wind tunnel located at the Ames Aeronautical Laboratory, Moffett Field, California. An asymmetric nozzle provides for Mach number variation from 1.2 to 2.0 while stagnation pressures can be varied from 3 to 20 pounds per square inch absolute. This wind tunnel has a 60,000-horsepower drive.

(3) The 16-foot transonic wind tunnel located at the Langley Aeronautical Laboratory, Langley Air Force Base, Virginia. Operation through the transonic range is at atmospheric density, only, with a drive power of 60,000 horsepower.

The designs of some smaller wind tunnels, notably, the 8-foot transonic and 4- by 4-foot supersonic at the Langley Laboratory and the 2- by 2-foot transonic at the Ames Laboratory have also contributed

further valuable information. However, of paramount importance in documenting NACA practices in the design of large wind tunnels are three of its new facilities currently under construction which embody the latest design philosophies and practices. Briefly these are:

(1) The 16-foot transonic wind tunnel at the Ames Laboratory. This facility is designed to operate through the transonic range up to a Mach number of 1.25. The variable-speed electric drive for the fan has 132,000 horsepower.

(2) The 10- by 10-foot Unitary supersonic propulsion wind tunnel at the Lewis Laboratory. A flexible-wall nozzle provides Mach number variation from 2.0 to 3.5. This wind tunnel is designed for closed-circuit aerodynamic testing at densities from 1.4 to 35 pounds per square inch absolute. For normal propulsion operation, suitable valving permits inlet of the entire air stream from the atmosphere through a dryer to the test section and exhaust through a silencer back to the atmosphere. The tandem axial-flow compressors have drive powers of 120,000 and 180,000 horsepower, or a total of 300,000 horsepower.

(3) The Unitary transonic and supersonic wind tunnel at the Ames Laboratory. The general arrangement of the facility is shown in figure 1 with an aerial view of the construction progress as of March 25, 1954 being given in figure 2. This facility provides for variation of Mach number from 0.7 to 3.5 in a total of three test sections having individual Mach number ranges of 0.7 to 1.5, 1.4 to 2.6, and 2.4 to 3.5. The corresponding test-section dimensions in order of increasing Mach number are 11 by 11 feet, 9 by 7 feet, and 8 by 7 feet. Special flow-diversion valves separate the two circuits for the supersonic test sections, thus permitting operation of each with the same eleven-stage axial compressor which has a maximum compression ratio of 3.5. To permit operation of the highest speed test section, the excess air from the compressor is bypassed around the nozzle and discharged through injector nozzles into the diffuser. The favorable effect that is produced in reducing the required compression ratio for the nozzle thus permits operation with the relatively low compression ratio available. The transonic test section is of the conventional type. In the Mach number range from 1.4 to 2.6, the speed is varied by use of an asymmetric nozzle. For the highest speed test section, Mach number variation is obtained by means of a modified flexible-wall nozzle which is later described in detail. Stagnation pressure is controlled in all circuits over a range from 3 to 30 pounds per square inch absolute. Power for the eleven-stage compressor and the three-stage fan which drives the transonic wind tunnel is obtained by coupling either the fan or compressor to the appropriate end of the main drive shaft. On this shaft are four tandem-mounted wound-rotor motors with a combined output of 216,000 horsepower.

The Ames Unitary facility has, because of its speed range, combined many design features which may be considered to be typical of NACA design philosophy. In the subsequent discussion of specific problems, the experience gained in that design will be cited frequently. Repeated reference to that design does not imply any particular superiority but has been done as a matter of convenience because of the intimate association of the authors with the project.

Selection of Components

The over-all requirements for a large high-speed wind-tunnel design are dictated by the type of investigations to be conducted. The dimensions of the test section and the Mach number range are specified to meet certain testing needs. Other factors which must be considered in specifying the wind-tunnel design requirements are: (1) the power available, (2) the cost, (3) the availability of manufacturing facilities for the components, and (4) the availability of adequate transportation to bring the components to the site. A detailed analysis of these limitations is necessary before the final design requirements can be set forth. Once such an analysis has been accomplished, the proper components can be selected and the detailed design can proceed. In general, the components to be selected are: (1) the flow generator or nozzle, (2) the diffuser, (3) the drive system (compressor or fan and its motive power), (4) the cooling system, (5) the model supporting system, (6) the pressure and humidity control systems, (7) the air passages and valving connecting the proper components, and (8) the test instrumentation. Each of these components, except the nozzle, may be dependent on one or more of the others, as will be noted, and the analysis of several types may be necessary in order to find those which are most suitable.

Nozzles

The starting point in the design of a large high-speed wind tunnel is the nozzle which generates the high-speed flow. The primary consideration is the choice of a nozzle which will give the required flow uniformity over the desired length of test section (or test rhombus at supersonic speeds). Two types of nozzles are commonly used for creating a supersonic air stream. These are the asymmetric, fixed-wall (see ref. 1) and the symmetric, flexible-wall nozzles. Figure 3 is a photograph of a model asymmetric nozzle while figure 4 shows the arrangement of a typical flexible-wall nozzle. Figure 5 shows the required variation of area ratio (area at the throat, A^*, to area at the test section, A_1) as a function of Mach number for supersonic operation. In the asymmetric nozzle the area-ratio variation is accomplished by a simple translation of one of the curved walls (preferably the lower) with respect to the other curved wall, the two side walls being straight and parallel.

It has been found that translation of the lower wall results in a simplified mechanical design. The direction of translation is parallel to the test-section longitudinal axis. In the flexible-wall nozzle the area variation is accomplished, of course, through distortion of the wall plates by means of jacks to fit the desired nozzle contour. Although the flexible-wall nozzles can be designed to cover almost any range of Mach numbers, it has been our experience that they are more adaptable to high Mach number operation where the range of plate deflections required becomes relatively small. Reference to figure 5 will show that a 62-percent reduction in throat area is required to obtain a test Mach number range of 1.0 to 2.5. Experience has shown that the flexible-wall nozzle must become extremely long to avoid very high bending stresses in the plates over this Mach number range. Conversely, the asymmetric nozzle for operation in this range can be relatively short and yet provide accurate flow. For a similar speed-range increment at the higher speeds, say Mach number 2.5 to 4.0, a reduction in throat area of only 29 percent is required and the opposite situation exists; the asymmetric nozzle which gives the correct flow becomes extremely long while the flexible-wall nozzle with a certain amount of preforming of the plates can be made comparatively short. The matter of length of large nozzles is a very important factor in the selection of the nozzle type, since the maximum size of steel plates which can be obtained from the rolling mills and the availability of machines of adequate size for machining them, as well as possible transportation difficulties, play significant roles in that determination.

The preliminary design of the nozzle shapes is accomplished by theoretical methods. Numerous methods are available for this purpose. References 1 through 3 and the references contained therein serve to summarize the methods used by the NACA. Whether symmetric or asymmetric, the nozzle flow fields are constructed in the hodograph plane and the coordinates of the contoured surfaces are then determined. This procedure for an asymmetric nozzle is given in detail in reference 2. The correction for boundary-layer growth is made as an average of the corrections for the extremes of the Mach number range by the method of reference 4. For asymmetric nozzles operating in the supersonic range below a Mach number of 2.5, this approximation has been found to be adequate. In the case of either symmetric or asymmetric nozzles operating at higher Mach numbers, some adjustment in angularity of the walls in the test section may be necessary to prevent an axial pressure gradient caused by the change of boundary-layer thickness with Mach number.

After the nozzle contours have been theoretically determined, it has been our practice to construct and test a working model of the nozzle. Experience has shown this procedure to be good insurance in guaranteeing the suitability of the actual nozzle. In the case of the design of the Ames Unitary facility, the models were generally about one-tenth to one-twelfth the size of the full-scale nozzles. Full operation of the movable lower block was provided in the model of the asymmetric nozzle.

Five fixed-block pairs of nozzles were constructed to simulate the flexible-wall nozzle at the highest, lowest, and three intermediate Mach numbers within its contemplated operating range.

Since the deviation of the flow from the direction parallel to the test-section axis is the controlling parameter in determining flow uniformity, establishment of limits of accuracy on this quantity will specify the uniformity required in other parameters such as Mach number and pressure coefficient. Experience has shown that a flow deviation of more than 0.2° is usually, but not always, unacceptable. The permissible deviation, of course, depends on the particular type of test to be conducted. Flow deviations of $\pm 0.1^\circ$ are considered to be the practical limit of accuracy. Any attempt to provide a more accurate flow will increase manufacturing costs far out of proportion to the increased flow accuracy obtainable.

Air-flow measurements within the model nozzles assess the variation of stream angle and Mach number over the entire test rhombus. Excessive variations are eliminated by refairing the nozzle contours. The success of the refairing process is a function of experience; generally, an experienced analyst needs to perform the refairing only once to obtain a satisfactory contour.

Figures 6 and 7 show typical test results obtained from the model asymmetric nozzle shown in figure 3. These data are for the nozzle as originally constructed and after modification of the nozzle contours. It will be noted that the relatively strong oblique waves seen in the schlieren photograph of figure 6(a) have been very nearly eliminated in the modified nozzle. In figure 7 the calculated variation of stream angularity is given for the modified nozzle to indicate the order of accuracy of the calculation method; this is seen to be approximately 0.2°. Since the method used was a graphical one, the accuracy of the calculations probably could have been increased by increasing the scale of the graphical work. The correction for growth of the boundary layer to eliminate the axial gradient in Mach number shown in figure 7 was made by inclining the upper wall of the nozzle to give slightly more divergence to the test-section top and bottom walls than was originally calculated.

In order to provide for continuous Mach number variation in the higher supersonic range and yet have a nozzle as short as possible, a somewhat different approach to the design of the flexible-wall type was undertaken for the nozzle used in the Ames Unitary facility. A schematic diagram of this nozzle is shown in figure 8. It will be noted that the upstream portion of the nozzle is a solid block having a circular-arc shape over most of its length. The circular arc is followed by an arbitrary curve having a smoothly changing second derivative from the circular arc to a section having no curvature at the region of inflection. The flexible plate attaches at this straight section and continues to the test section. This arrangement was considered practical because the

method of design used permits the choice of any arbitrary shape upstream
of the point of inflection in the nozzle contour. Before an aerodynamic
model was constructed, a full-scale, 5-inch-wide mechanical model of the
flexible plate and attaching block was built. Results of these tests
showed that faired curves, smooth in their second derivatives and dupli-
cating the required nozzle contours, could be produced. The mechanical
operators for this type of nozzle consist of screw jacks on both plates
and blocks. The blocks must have some freedom both to rotate and to
translate. The axial load which otherwise would be transmitted by the
block into the plate is resisted by a series of servo-operated hydraulic
jacks placed between the blocks and a supporting frame.

Tests of an aerodynamic model with an 8- by 6-inch test section and
having fixed nozzle blocks, which represented the nozzle contours for
several Mach numbers, and calculated as outlined above indicated that
sufficiently uniform flow could be obtained. In figure 9 it will be
noted that the variations of static pressure coefficient and stream angu-
larity at a Mach number of 3.5 were found to be within acceptable limits.
It was determined that further correction to the Mach number gradient
could be achieved by revision of the contour in the region of the flexible
walls. Similar results were experienced at other test Mach numbers
ranging as low as 2.4. It should be noted that refairing of the model
nozzle contours was not considered necessary because it was expected that
any required flow modifications could be obtained at full scale by
adjusting the position of the flexible walls.

With regard to construction methods used in nozzles of large sizes,
it has already been mentioned that the availability of manufacturing and
transportation facilities is an important consideration. Added to this
must be the time required for construction since no research facility
has any value as an engineering project in itself. Rather, the emphasis
on engineering ingenuity to construct the facility in the shortest pos-
sible time must be of extreme importance so that the planned research
for which the facility has been designed can commence. It is necessary,
therefore, to design these large nozzles so that they can be manufactured
rapidly with the needs for special tooling kept to a minimum. Further,
it is required that the individual parts be made small enough to be
readily transported to the site for final assembly. The foregoing con-
siderations can best be demonstrated by reference to a few examples which
have been experienced in the design of the Ames Unitary facility.

The asymmetric nozzle which is used in the Ames Unitary facility,
figure 10, has a movable lower wall which is 87 feet in length. The
contoured portion of this wall is 50 feet long while the contoured por-
tion of the upper wall is 62 feet in length. Although these contours
remain fixed in operation, it was immediately apparent that they could
not be made as one-piece structures because of the transportation prob-
lem. Further, even though it might have been possible, with special
tooling, to machine fixed weldments in several sections to the desired
contour, it was not considered good design practice to do this for two

reasons: (1) the time required and attendant costs and (2) the possibility that it might be desirable to make slight modifications in the contours after the nozzle was placed in operation. As a result, the contoured surfaces are constructed from 1/2-inch-thick plates worked flat and uniform in thickness and attached to a heavy steel framework by means of studs resistance welded to the back of the plates. This construction is shown in detail in figure 11(a). The actual nozzle contour is produced by bending the plates to their desired positions through operation of the turnbuckles as indicated in the figure. The supporting heavy framework can then be constructed at final assembly by ordinary steel construction methods and with the normal tolerances for work of that type. This method of producing a curved wall, in general, will necessitate at least one pair (upper and lower walls) of joints at the leading edge of the test section in the supersonic air stream. This is because of manufacturing limitations on the obtainable plate sizes. Extreme care must be taken in working these joints to the proper fairness at final assembly. However, experience has shown that with proper workmanship such joints can be made to have no effect on the flow.

The design of the flexible-wall symmetric nozzle previously mentioned was influenced also by manufacturing and transportation considerations. Indeed, the aerodynamic design used was necessary in order to keep the flexible plates to a size which could be produced in one piece without welding. Although welding is not considered entirely undesirable, the particular alloy steel used in these plates was of such recent development that the required experience in welding procedures was not at hand. Welding was, therefore, avoided insofar as possible. Of course, the T-stiffeners on the back of the plates to which the jacks attach, as shown in figure 11(b), were welded to the plate before machining. The stresses in these welds were quite low; however, as a matter of interest, some difficulty was experienced in satisfactorily making these welds without cracks.

The problem of surface finish in these large nozzles has always been one of concern because of the special tooling required to grind such extensive surfaces. No rigid specification of an acceptable finish is known, the usual approach being to get the best surface possible which is probably in the vicinity of 16-microinches root-mean-square roughness. To obtain such a finish by grinding is extremely tedious.

In a normal supersonic wind tunnel used for aerodynamic testing at normal temperatures, it has been found that a perfectly acceptable surface can be obtained in the following manner. The surfaces are machined or, if no machining is necessary, they are sandblasted to give a surface roughness of from 125 to 250 microinches. The surfaces are then thoroughly cleaned and given a coat of metal primer such as zinc chromate. This coat of paint is rubbed smooth by the usual methods and a second coat applied which is also rubbed smooth. If care is taken and the paint not applied too thickly, the resulting surface can have a roughness no greater than 10 microinches.

In a propulsion wind tunnel, which may be open to the atmosphere
and exposed to corrosive combustion products, painting of the interior
surfaces is not an adequate method for obtaining smooth interior surfaces.
Usually the material used in constructing the air passages must be stain-
less steel which will, in itself, give adequate corrosion protection.
Grinding of the interior surfaces of the nozzle and test section to the
required degree of smoothness is usually required in this instance.

The cost of large wind-tunnel nozzles is very difficult to estimate
because of the wide variations between designs. In general, the nozzle
design to be constructed by existing manufacturing equipment will be
cheaper than that which requires special tooling. The degree of com-
plexity of the mechanical equipment required to operate the nozzle also
affects the cost. No standard rule can be used in estimating nozzle
costs but experience has shown them to be in the range of from $1500 to
$2500 per ton, depending on the complexity of design and availability
of manufacturing facilities.

Diffusers

The diffuser for a wind tunnel capable of variable Mach number and
continuous flow can be chosen on the basis of the compression ratio
required to maintain supersonic flow at the highest Mach number. Super-
sonic flow can be established at or near the minimum operating Mach num-
ber so that no starting problems are encountered. This manner of opera-
tion is not particularly characteristic of large wind tunnels - any wind
tunnel of the type under discussion, irrespective of size, can be operated
in this fashion.

In the case of a wind tunnel intended primarily for aerodynamic
(rather than propulsion system) investigations, the model will generally
be supported from the rear by means of a cylindrical member called a
sting. The supporting structure for the sting must be mounted in the
diffuser downstream of the test section and, thus, the design of the
model support system will affect the general arrangement of the diffuser.
A typical installation of this type is shown in figure 12. The model
supporting system and the diffuser must be considered as an integrated
unit in the design of the wind tunnel. This is especially true at the
lower supersonic Mach numbers where improper design can cause the dif-
fuser to choke with consequent loss of supersonic flow.

The avoidance of choking in the region of the model support at
transonic and low supersonic Mach numbers has been investigated in a
number of model wind tunnels. These investigations have shown that suf-
ficient area must be provided by expanding the diffuser cross section
so that the Mach number in the region of the model support does not fall
below a value of approximately 1.25. In estimating the required area to be
added to compensate for the presence of the model support, the growth of

the boundary layer along the diffuser walls must be taken into account. Since this is a rather complex problem because of the effect of the model support's own shock-wave system in creating adverse pressure discontinuities at points where the system intersects the walls, it has been found most expedient to develop the diffuser and model support configuration experimentally.

A second consideration affecting the choice of the diffuser configuration is the additional disturbance to the diffuser operation created by the presence of the model itself, especially if the model is large and at a high angle of pitch or yaw with an attendantly strong shock system. Figure 13 gives the results of tests made to determine the minimum operating compression ratio as a function of Mach number for various combinations of diffuser, model support, and triangular-wing model with a symmetrical double-wedge section of 4.7-percent thickness, as shown in figure 12. Placing the model at a pitch angle of 30° had a pronounced effect in increasing the operating compression ratio. It should also be noted that the minimum operating Mach number for this model wind-tunnel arrangement, figure 13, increased from 1.5 with the model at 0° angle of attack to about 1.8 when the angle of attack of the model was increased to 30°.

In the design of diffusers for transonic wind tunnels a paradox exists. To maintain the operating power at a minimum it is desirable that the operating compression ratio be as low as possible. This will require that the Mach number in the diffuser be maintained at about that of the test section. However, to avoid the presence of detached shock waves in the test section caused by the model support system which is located in the diffuser, it is necessary to accelerate the flow at the entrance to the diffuser to a sufficiently high Mach number to prevent detachment of the model support's shock-wave system. Of course, this latter requirement must take precedence over the former to insure reliable test results. As a consequence, the relatively low operating compression ratios required for transonic wind tunnels (as compared with supersonic) with so-called "clean" or unobstructed diffusers cannot be utilized unless some different, and as yet not obvious, method for supporting models is devised.

In the design of the supersonic portion of wind-tunnel diffusers, it has been shown in figure 13 that by proper design of the model support system, no serious penalties in operating compression ratio will be incurred and, hence, the power required will be little affected. The effect of the model itself must be properly compensated by increase in compression ratio, but this effect is considered to be small enough to fall within the normal margin of compression ratio available over that required; however, it is always possible to attempt to test a model large enough to prevent operation. No consideration has been given here to the actual diffusion of the supersonic air stream. It is this process that may require as much as 95 percent of the power in a supersonic wind tunnel. There are considerable published data on this aspect of

diffuser design (see refs. 5 to 7) which have been substantiated by tests at Ames Laboratory and elsewhere. These data have been used as the basis for obtaining the appropriate over-all supersonic diffuser design as outlined above. It is sufficient to mention here that at the highest operating Mach number, it is always desirable to have the terminal shock wave occur at the lowest possible Mach number. Further, it is desirable that the terminal shock wave occur in a region of the diffuser, free from adverse pressure gradients.

With regard to the subsonic portion of the diffuser, experience has shown that lower losses will be encountered if the diffusion process is started very slowly just downstream of the terminal shock wave and allowed to progress more rapidly as the flow decelerates. This is in accordance with the results given in reference 5. A diffuser having more or less the shape of a trumpet is the result. This shape has been modified in large designs to that of a series of tandem-connected cones each having a progressively larger angle of divergence so as to avoid double curvature in the diffuser wall plate which may have a thickness of 1 inch or more. The double curvature presents forming problems in which inaccuracies caused by construction can have greater adverse effects on the flow than that of the slight change in angle between conical sections.

Subsonic Air Passages

The remaining losses in the wind-tunnel circuit which must be taken into account before the compressor system can be selected are those contributed by skin friction throughout the subsonic air passages, by the aftercooler, turning vanes, and screens (usually safety and possibly antiturbulence). These losses can be kept to a minimum by designing the subsonic passages to have low velocities. The velocities given below may be considered typical:

Corner at end of diffuser.	250 feet per second
Special valves	100 feet per second
Other corners.	50 feet per second
Settling chambers.	25 feet per second
Upstream face of coolers	10 feet per second
Upstream face of safety screens. . .	120 feet per second
Upstream face of first antiturbulence screen	15-20 feet per second

It should be noted that these values are used for the condition of maximum Mach number. They will increase because of the greater mass-flow requirements as the Mach number is reduced. In any event, the losses from these sources are small enough, compared to those of diffusion of the supersonic air stream, that calculation with ordinary engineering accuracy is sufficient to determine the over-all losses in the wind tunnel.

The design of the aftercooler, which accounts for the majority of these remaining losses, generally is the subject of some conjecture. If a diffuser of small divergence angle is used to bring the stream to the low velocity required, then the wind-tunnel circuit becomes extremely long. On the other hand, if a wide-angle diffuser is used in combination with heat-transfer surfaces having a relatively high resistance to the flow, so that the diffuser will fill properly, then a higher loss may be encountered. It has been found from experience that the total loss encountered is so small, in either case, as to make this argument academic; therefore, the design is usually based upon economic considerations.

Compressor Selection

Once the maximum and minimum required compression ratios and test-section size have been determined, it is necessary to examine the various compressor systems available for operation of the wind tunnel over the required Mach number range. In general, it will be found that any particular compressor design will have a limited range of flow quantities in which it is capable of operation for fixed settings of the blading. Thus, it may not always be possible to operate over the entire test-section Mach number range without resorting to some method, such as (1) staging compressors, (2) bypassing a portion of the discharged flow, (3) variation of speed, or (4) variation of blade angle. In order to study this problem the construction of a chart,[3] such as that shown in figure 14, is helpful. The construction of this chart, which relates the characteristics of the wind-tunnel throat and compressor through the equation of continuity, is based on the analysis given in reference 8 and is a modification of the chart presented therein. Other forms can be used to suit the needs of a particular design; this form has been used here because of its convenience in dealing with single-stage variable-speed compressor operation. The compressor must operate on its characteristic curve as shown in the lower left-hand plot. Operation of the wind tunnel is possible if available compression ratios lie on or above the nozzle characteristic curve shown in the lower right-hand plot. A point on the compressor characteristic curve (point A on chart) can be connected to a corresponding point of equal mass flow for the nozzle by constructing straight lines (shown dotted) to points B and C on the curves, derived from continuity, shown in the upper portion of the chart. A vertical line through C, then, defines the operating Mach number. If the intersection of the vertical line through C with a horizontal line through point A, the compression ratio chosen, occurs above the wind-tunnel characteristic curve, as in the case of point D, then the terminal shock wave will be forced down the diffuser until the chosen compression ratio is reached. Different sets of intersecting lines may be constructed for different compressor speeds or for different compressor characteristics entirely, and the complete range of possible wind-tunnel operation

---

[3]Construction of this chart was originally proposed by W. G. Vincenti of the Ames Aeronautical Laboratory.

can be explored. Guidance in varying the compressor characteristic is
obtained from the constant Mach number lines on the compressor charac-
teristic plot. The compressor efficiency contours permit rapid calcu-
lation of the power requirements.

It is of interest to note that under certain circumstances, as was
the case in the Ames Unitary facility, the selection of the compressor
may not be entirely flexible. Here, the rotor diameter was limited by
the maximum diameter (18 feet) to which the discs could be forged. Also,
the most economical electric motor speed was found to be approximately
700 revolutions per minute. Thus, only compressors designed to these
limitations could be considered, with a resulting narrowing of the
choice of the compressor characteristic curves. In this case the chart
was used to study variations of test-section area and stagnation tem-
perature, both of which affect the location of the curve in the upper
right-hand plot. It is also of interest to realize that for a fixed
compressor design, an increase in tunnel efficiency through better
supersonic diffusion will usually provide an increase in operating Mach
numbers only if the test-section size or stagnation temperature is
increased. (See points C' and D'.) For a fixed operating Mach number
away from the compressor design point, an increase in diffuser efficiency
will only serve to force the terminal shock system farther down the dif-
fuser unless the added efficiency can be utilized by a change of compres-
sor speed or blade setting.

The matching of the wind tunnel and the compressor characteristics
is principally a matter of trial and error. The first choice the
designer must make is that of the range over which a single machine must
operate. (For the large wind tunnels under consideration the use of
centrifugal compressors is virtually eliminated because of the multi-
plicity of machines and the complicated valving and piping required; thus,
the discussion will be confined to axial-flow-type machines.) In gen-
eral, the wider the range selected, the poorer will be the compressor
efficiency at points far from the design point; indeed, the requirements
for high mass flows at the lower compression ratios can cause choking
in the compressor exit stages unless the compression ratio per stage and,
hence, velocity is kept low. This last consideration leads to an inor-
dinately large number of stages for the compressor and can produce a
situation where the mechanical design is virtually impossible. Exper-
ience indicates that the design of a single machine with more than 11
or 12 stages would be exceedingly difficult. The choice of compressor
range will determine whether or not staged machines will be required.

The use of staged machines will permit the designer to match the
compressor system to the wind-tunnel characteristics once for each stage
used. Within each stage the wind-tunnel characteristic curve may be
more closely approached if blades are provided which can be varied in
angle during operation or if variable-compressor speed is provided. The
complexities associated with either variable-rotor or -stator blade angle
or both have been considered too costly and impractical mechanically by

NACA designers of large compressors and, hence, this method has not been used. The expense and somewhat added electrical complexity of variable-compressor speed are thought to be warranted to attain a closer matching of the wind-tunnel characteristics.

In some instances the use of a bypass to provide a better matching of wind tunnel and compressor is desirable. This is primarily dependent on the choice of the compressor system which is used. As mentioned earlier, this system usually is not entirely flexible. It was found in the design of the Ames Unitary facility that bypassed air introduced through injectors into the diffuser of the highest Mach number circuit could reduce the required compression ratio enough to permit operation of the wind tunnel with a compressor designed primarily for operation of the lower speed supersonic circuit. This circumstance may be fortuitous and, of course, much better Reynold numbers could have been obtained with a compressor which was designed for the higher Mach number circuit alone since, at the highest Mach number, this wind tunnel has a characteristic which requires that approximately two-thirds of the compressor discharge volume be bypassed at the maximum compression ratio. In any event this compromise of performance, compressor design, and cost is typical of those made in wind tunnels of this size.

Compressor Design

No attempt will be made to present the general design methods for axial-flow compressors as these are well known; however, it is of interest to discuss one specific design - that of the eleven-stage machine for the Ames Unitary facility - because it is considered to be representative of the philosophy underlying the design of very large axial-flow compressors.

The choice of design point for the Ames machine was made after the required compression ratio and mass flow had been estimated as discussed previously. An excess margin of compression ratio of about 0.05 was allowed above that estimated for the highest anticipated Mach number. Because the compressor was to operate with a variable-speed drive, a design speed 3 percent below the maximum was chosen. This would provide for a further margin of increase in the maximum compression ratio available by increasing the compressor speed.

The number of stages was determined by selecting a compression ratio of 1.12 per stage. It is realized that this value is rather conservative but it was thought that such a value could be readily obtained without resorting to extremely close tolerances in the construction of the flow passage and blades. Further it was believed that the design would be less critical to flow conditions at points other than the design point so that a wider range of flows could be tolerated without surging or choking.

The over-all adiabatic efficiency of the compressor was chosen to be 81 percent. This value was based on test results of smaller compressors having approximately the same number of stages.

With the foregoing conditions fixed it was then possible to establish the compressor size by determination of the entrance area. As has been pointed out earlier, a limit of 18 feet on rotor-disc diameter was imposed by manufacturing capabilities and the drive motor maximum speed of 685 revolutions per minute was fixed by economic and electrical design considerations. It was also apparent that a smaller diameter rotor could not be designed to accommodate a sufficient number of blades to absorb the required horsepower as calculated from the mass-flow requirements. It was, therefore, a problem of selecting a tip diameter for the first-stage blades which would permit the use of reasonable values of air-flow turning angle, design camber, solidity, and tip Mach number. Equations can be written defining these parameters either in terms of the hub to tip diameter ratio, mass flow, and power absorbed, or relating them to one another. It was thus possible to prepare charts of axial Mach number, blade-tip Mach number, mean air turning angle, and the product of solidity and blade lift coefficient all as functions of tip radius. By use of these charts and by imposing certain other limiting conditions based on previous experience and known to be conservative, the blade-tip diameter for the first stage was chosen to be 22 feet. These additional conditions were: (1) the power absorbed in the first stage would be 10 percent higher than the average for all stages, (2) the blade-tip Mach number must be below 0.63, (3) the axial Mach number must be no greater than 0.40, (4) the mean air turning angle at the mean radius of the blade should be less than 45°, and (5) the product of solidity and lift coefficient should be 1.2 or less.

It has been our experience that the mechanical design and construction of large axial-flow compressors are simplified if the rotor diameter is kept constant throughout its length. Even had the rotor-disc diameter not been limited, a machine having a constant-diameter rotor would probably have been chosen. Thus, the selection of the exit area for the compressor became one of selecting a shorter blade-tip diameter for the blades of the last stage. In the case of the machine under discussion, the limiting requirement was that the blade-tip Mach number should not exceed 0.7 when the compressor was operating at the off-design point which required the largest mass flow. As mentioned previously, there is a possibility of choking in this region if sufficient exit area is not allowed.

In the design of the compressor blading, the vector diagrams of the velocities were made approximately symmetrical for the mean radius station of each stage and were selected throughout for free vortex flow. The design method was suggested by Maurice Tucker of the Lewis Flight Propulsion Laboratory of the NACA. The selection of blade camber and twist was made on the basis of design data obtained at the Langley

Laboratory in the cascade wind tunnel described in reference 9. Additional information was obtained from reference 10. The following design limits were used:

Solidity. . . . . 1.0 to 1.5
Design camber lift coefficient. . Less than or equal
to 1.5
Aspect ratio. . . . . 2.0 or greater
Number of blades. . . . . An even number with
the number of rotor
blades different
from either the
preceding or fol-
lowing sets of sta-
tor blades

It was possible by judicious selection of design camber, solidity, and twist to select one blade design which permitted all rotor blades to be identical except for cutoff length. A similar uniform design was obtained for the stator blades. The design was completed with a set of entrance vanes and a set of exit vanes.

The foregoing approach has been used to affect the design of several other large axial-flow compressors. Two of these machines, now in operation, are shown in figure 15. The compressor used in the Ames 6- by 6-foot supersonic wind tunnel has eight stages and a rotor diameter of 12 feet. The compression ratio is 2.2. The Lewis 8- by 6-foot supersonic propulsion wind tunnel compressor has seven stages and a rotor diameter of 13 feet, 2 inches. Its compression ratio is also about 2.2. In addition to the Ames Unitary facility compressor described above, two other machines for the Lewis Unitary facility are now under construction. These machines have ten and eight stages. The respective compression ratios are 2.4 and 2.8.

The mechanical design of these machines follows generally the practices used in the design of steam turbines. Each rotating stage has its blades attached at a fixed angle to the rim of a disc. Spacers are located between discs to give the proper stage spacing and the entire assembly is made a unit by through bolts which extend the full length of the rotor. The stationary blades are made manually adjustable in angle. In some instances shrouds have been used on the inner end of the stator blades, the shroud band being between rotating rows and thus forming a part of the inner periphery of the air passage. In other cases the rotor has been built up to have a continuous cylindrical surface and the stator blades are supported only at their outer ends. The latter method gives a somewhat cleaner aerodynamic design while the former provides simpler rotor construction with apparently no great sacrifice in performance for a machine of relatively low pressure rise per stage.

Rotor blades have been constructed from 14 ST aluminum alloy and steel. Because of its relatively poor fatigue resistance, especially at elevated temperatures, the use of aluminum alloys is not recommended. Hollow blades of high-strength steel have been used in one machine but are not recommended unless the manufacturing processes now used can be further refined to eliminate points of stress concentration in the built-up sections of the blades. Further, the cost of this type of blade is relatively high. It is believed that the most satisfactory designs are those having solid, alloy steel (12-percent chrome) blades with discs of sufficient strength to withstand the higher centrifugal forces. While it is realized that special machines must be used to contour solid-steel blades it is believed that this disadvantage is outweighed by the greater reliability afforded through minimizing vibration and high-temperature problems. It should also be pointed out that the special tooling for contouring will be less expensive than that required to produce hollow blades even of inferior dimensional quality.

Stator blading of cast steel has proven satisfactory. Careful processing can permit the contoured section, except in the vicinity of the leading and trailing edges, to be cast nearly to final dimensions. Machining of the contoured section is then limited to relatively small areas and can be done quite simply. The final contour can be achieved without great effort by hand-grinding. Of course, the points of attachment for the blades must be machined.

It is considered essential that as much of the blading as possible, both rotating and stationary, be examined for vibration characteristics during initial operation. This is done through the use of electrical strain gages attached to the blades. Provision for this instrumentation must be considered during the compressor design.

The costs of special machines like these compressors are exceedingly difficult to estimate. Succeeding designs are usually enough different from each other so as to preclude an accurate estimate based on experience. Exclusive of blading, it is probable, however, that the cost of a large axial-flow compressor will not exceed a price of $3000 per ton of finished weight. The cost of blading depends on such a variety of design and construction factors that no representative cost figures can be cited.

Power Systems

All of the large high-speed NACA wind tunnels are electrically powered. Studies of other types of power, for example, direct water power or either steam or gas turbine, have shown that the applications of these types are limited to certain special conditions which do not exist at any NACA laboratories. On the other hand, all the laboratories are excellently situated with respect to sources of electrical power.

Thus, experience with large electrical loads had been gained, even prior to the design of any large high-speed wind tunnels, through the operation of large subsonic facilities. In general, the power systems used in the newer high-speed facilities have been expanded versions of systems used previously.

It was mentioned above that there are certain advantages to a variable-speed power system for supersonic wind tunnels using axial-flow compressors. This type of system is also considered desirable for operation in the transonic range. If a system having the relative simplicity of fixed blade-angle compressor construction and the proven reliability of a certain variable-speed electrical drive is weighed against a system having a constant-speed electrical drive and variable-angle compressor blades, no great cost advantage for either type of system is evident. However, the variable-speed system will permit greater flexibility of operation. These considerations have been the basis for the selection of that type of system for the large high-speed wind tunnels of the NACA.

Of the various types of variable-speed electrical power systems available, only two, (1) the modified Kramer and (2) the slip regulator, lend themselves to high power applications. Schematic diagrams of these systems are shown in figures 16 and 17. In the modified Kramer system the wound-rotor drive motor is doubly fed - the primary is energized directly from the power line while the secondary is energized from the output of a variable-frequency generating system. The speed control, efficiency, and power factor of this system all are excellent but the cost is high. On the other hand, the slip regulator system, which employs a wound-rotor induction motor with speed control being afforded by changing the rotor circuit resistance, is less costly than the modified Kramer system but has certain disadvantages which must be considered. The resistance variation in the slip regulator system is usually accomplished with liquid rheostats. Under conditions of low slip, the power loss in these rheostats is low and the system efficiency and power factor are relatively high. However, at high slip the power loss in the rotor circuit is high and the efficiency and power factor are low. In addition the slip regulator system can provide no negative torque and additional equipment is required to decrease the speed rapidly.

In the design of a wind-tunnel power system certain considerations will influence the type of system to be selected. Among these are: (1) the effect of rate of power increase or decrease on the power network, (2) the precision of speed control required, (3) the range of speeds required, (4) the power factor which must be maintained, (5) the size of rotating machines which can be constructed, and (6) the cost. In a variable-density wind tunnel the rate of power increase can be adjusted by controlling the rate of density increase so that this consideration need not affect the electrical-system selection. Also, because of the steady nature of supersonic flow, precise speed control is not important unless the compressor is very near the surge point and, likewise, the speed range in which variation is required is not great. Conversely,

the satisfactory operation of a transonic wind tunnel places very stringent requirements on the speed control and range of the electrical system. Consequently, the selection of the power system must be the result of a study of all known requirements, and experience has shown that each different wind tunnel will have a unique system. This is exemplified by the diagrams of figures 18 and 19 which show the systems used in the Ames Unitary facility and the Ames 16-foot transonic wind tunnel, respectively.

Actually the system used in the Ames Unitary facility introduces the feature of high-speed electronic regulation which has not been used heretofore in wind-tunnel drives. This may be considered a modification of the slip regulator system which can give speed regulation essentially equal to that of the Kramer system. However, the efficiency of the modified slip regulator system at low speeds (high slip) is low compared to that of the Kramer system. It will be noted that a dynamic braking motor-generator set is incorporated into the modified slip regulator system to provide the necessary negative torque. Originally it was intended to provide control of this system by having a modified Kramer control for one of the four motors because the electronic regulation system was untried. However, cost analysis indicated that an additional cost of approximately $1,000,000 would have resulted had the Kramer system been used. In the drive system of the Ames 16-foot transonic wind tunnel, additional expense was not incurred because the Kramer control elements were available. This came about because this wind tunnel is a modification of an older high-speed wind tunnel which incorporated the modified Kramer control system in the drive. The system shown in figure 19 was designed to incorporate these elements as indicated.

The power network which serves the wind-tunnel drive system may, itself, greatly influence the design of the system. Conditions of frequency and voltage fluctuations, network stability, and short-circuit capacity are of importance. Frequency variations are, in general, inclined to be in the nature of long-period drifts. This is not generally critical, as was pointed out above, to operation of supersonic wind tunnels. Variable-speed power systems, for transonic wind tunnels will find frequency drifts objectionable, however, if the frequency period is sufficiently short as to interfere with the model testing. Voltage fluctuations can be either of the transient or long period varieties. Voltage fluctuations of a transient nature or of low magnitude should not seriously affect supersonic wind-tunnel operation. The transonic wind tunnel, on the other hand, can be seriously affected by speed fluctuations caused by voltage variation. The modified Kramer system can be made relatively independent of both frequency and voltage fluctuation by suitable fast response control of the direct-current circuit interposed between the power system and the drive motors. On the other hand, slip regulator controlled wound-rotor motors are particularly sensitive to such fluctuations, especially if operating at considerable slip. Even in the case of the slip regulator drive, however, the usually

high inertia of the compressor will tend to smooth out many disturbances of short duration, and the slip regulator electrodes may be automatically adjusted to help maintain a desired speed.

The stability of the serving power network must also be considered since the loads imposed by a large wind-tunnel drive may form a considerable percentage of the total power in the network. It is quite possible that network instability can seriously impair the wind-tunnel operation as the magnitude of the serving power network and the magnitude of the rating of a large wind-tunnel power system impose severe short-circuit conditions which must be factored into the design of the electrical system.

The size of the motors employed for modern large wind-tunnel drive systems is such that little choice is available in the voltage rating of the motors. Wound-rotor motors are quite effectively limited to the 6900-volt class by power factor considerations. Very little is left to choice in the matter of motor speed since the compressor design usually demands as high a speed as is practicable. The centrifugal force on the windings, particularly in the case of the wound-rotor motors, is the limiting factor. When the desired compressor speed exceeds that which can be tolerated by the motor, gears must be employed. Other considerations will apply where drive systems incorporating synchronous motors are used.

Wind-tunnel power systems are normally stopped and started by means of high-voltage (15-kv class) air or oil circuit breakers. Inasmuch as 2,000 to 3,000 operations per year can be expected, these stop-start circuit breakers must be of an extremely rugged construction. To achieve this ruggedness and dependability the so-called "steel-mill" type of 15 or 7.5 kv, 500,000 kva, interrupting capacity circuit breaker has been used. Higher voltage circuit breakers, usually oil, for the control of the transformer primaries are usually of the 110 to 138 kv substation type. Wind-tunnel-drive auxiliary motors are usually 440 volt or 2300 volt, or even higher, depending on the size of the particular units.

The magnitude of the power handled in a large wind tunnel is such that, because of the relatively low motor voltage, the large currents preclude, from any economic standpoint, any extensive distribution at motor voltage level. This means that the transformers must be placed close to the motors (perhaps within 200 feet). When it is necessary to locate the power transformers at the wind tunnel, the high voltage feeders must sometimes be brought in underground, employing cables with a voltage rating at 110 kv or higher.

The operation of large wind tunnels must be integrated with the power network if the cost of extra generation is to be avoided. Wind-tunnel loads are usually of a high-demand, low-load-factor character. This means that large blocks of power must be employed but only for relatively short and infrequent intervals. It is possible to schedule

wind-tunnel operations so that the wind tunnels may utilize system generation, which is not being employed at that time, merely by avoiding the system load peaks. Telemetering and load control equipment is required to enable this operation.

Other Wind-Tunnel Components

Completion of the selection of the nozzle, diffuser, model support system, and drive system of the wind tunnel will generally establish the design requirements of the remaining components. Assumptions made in determining losses must be met in the design of the connecting circuit and in the compressor aftercooler. The design of the aftercooler will be further limited by the estimated range of compressor-discharge temperatures and the power-input characteristics of the electrical power system. The pressure control system will have to meet certain requirements of the power system with respect to rate of increase and decrease of load. The design of special valving and other special components must be compatible with assumed losses and with the integrity of the wind tunnel as a complete structure.

An aftercooler for the compressor can be assembled from commercially available heat-exchanger units. These units can be arranged in a variety of ways in the air stream to suit the pressure drop and maximum cross-sectional-area requirements as dictated by other design considerations. The commercially available units are usually rectangular in shape, and the cooling surface consists of thin fins of copper or aluminum bonded to copper tubing through which water is circulated by means of headers located at each end of the tubes. In several Ames Laboratory designs, it has been found convenient to stack these units so as to fill as nearly as possible the circular cross section of the cooler shell. All units are operated in parallel with the heat-exchanger stack being only one unit in thickness. Adjacent stacks of units are staggered axially to permit access to the headers on the ends for piping cooling water to them. All of the cooler cross section not included within the heat-exchanger pattern is carefully baffled to prevent bypassing of the exchangers.

The common cooling medium is water which is circulated through the heat exchanger units by electrically driven pumps. Flow to the individual units is controlled by valves which are adjusted manually until the desired uniformity of temperature is obtained in the air stream. Generally, a temperature pattern deviating by less than 2° F from the mean temperature is considered satisfactory. The entire water flow is controlled by valves having temperature-sensing elements and which regulate the stagnation temperature in the settling chamber to a uniform value within about 1° F of the selected value.

Cooling of the water can be accomplished through use of a cooling pond in locations where water is plentiful and cool. For more arid

locations, such as that of Ames Laboratory, an evaporative-type cooling tower is more practical and economical.

The pressure control system of a supersonic wind tunnel provides control of the Reynolds number. In addition, this system can be designed to give humidity control and control of the rate of power increase. The humidity control in a supersonic wind tunnel can easily be accomplished by removing the atmospheric air and replacing it with dry air.

The equipment required to perform this operation will include an air compressor with aftercooler, a dryer, and an evacuator. Some moisture will be removed from the air in the aftercooler by condensation. It has been found economical to use several stages of refrigeration to increase the volume of the condensate, thus permitting the use of a smaller dryer. The dessicant used in the dryer can be silica gel or activated alumina. If the dry air can be stored independently, the compressing system used for its production can also be made to serve as the evacuation system for removing the atmospheric air from the wind tunnel. To accomplish this dual service, the compression ratio of the system should be about 10.

It has been found economically feasible to use the system just described in connection with large supersonic wind tunnels and yet keep the drying cycle of the air circuit to a reasonable time. A typical cycle consists of charging storage tanks with dry air at 165 pounds per square inch absolute and, then, using the centrifugal air compressor as a vacuum pump, removing the atmospheric air by evacuation of the wind tunnel to 1.5 pounds per square inch absolute. The size of the compressor will, of course, be dictated by the time required for the cycle. In the case of the Ames Unitary facility, this compressor has an inlet volume of 50,000 cubic feet per minute and requires 15,000 horsepower. The evacuation time is 17 minutes for a wind-tunnel volume of 400,000 cubic feet. The stored air, equal in volume to that of the wind tunnel at atmospheric pressure, is then introduced into the wind tunnel. The humidity for high Mach number operation should be kept to a maximum not exceeding 0.0001 pound of water per pound of dry air. If this humidity is not achieved in the first cycle, a second purging operation is required.

The control of the rate of power increase and decrease is afforded by valving of the charging air on increasing power and by the evacuation rate obtainable in the auxiliary compressor system for decreasing power. It should also be mentioned that this mode of operating the wind tunnel permits starts at low density to avoid high loads which could be imposed on the model as the terminal shock system moves through the test section. The same consideration applies in stopping the wind tunnel.

A certain amount of leakage requires control of the stagnation pressure during operation of the wind tunnel. Additional air required to make up for outward leakage is supplied from the dry-air storage tanks. To control inward leakage from seals, such as that used on the

compressor drive shaft where dry air is bled into the circumferential opening to prevent entrance of atmospheric air, a small separate source of vacuum, usually pumps, is provided. Control of the stagnation pressure is normally accomplished by means of a pressure-sensitive servo-operated control system which is designed to maintain this pressure constant at the desired value to within 1.0 millimeter of mercury.

Under certain circumstances, such as occurred in the design of the Ames Unitary facility, special components will be required which cannot be assembled from commercially available products as is generally the case with the cooling and pressure control systems. In the case of the Ames design, a pair of special flow-diversion valves was required because of the dual service planned for the eleven-stage axial-flow compressor. It was thus necessary to develop a design which promised assurance of operation before the final design of the wind tunnel could proceed. The principle of operation of the plug valve was used in the design of these flow-diversion valves, one of which is shown in figure 20. In this photograph the valve has been rotated to receive flow from the wind-tunnel circuit seen in process of attachment at the right. The passage at the left is seen to be blocked. The guide vanes are a circular arc of 90°. One section of these vanes has been omitted for installation of the compressor drive shaft about whose axis the valve core rotates. Operation of these valves occurs only in the absence of air flow. Another example of special equipment is the disconnect couplings required at each end of the drive-motor shaft of the Ames Unitary facility.

Structural Considerations

The structural design of all wind-tunnel components is usually based on a code controlling the design of unfired pressure vessels insofar as such a code will apply, except in the design of nozzles and compressors where deflections are controlling and the structure is designed accordingly. Where a code is not applicable, conservative design practice with a generous safety factor is considered prudent. Since most variable-density supersonic wind tunnels must be designed to withstand a full vacuum, because of humidity control considerations, this condition will control the design of the shell and stiffener rings so long as positive pressures of less than 4 to 5 atmospheres are encountered. In large wind tunnels, pressures of this magnitude will require tremendous amounts of power so that the vacuum condition will generally control the design. This is not true, of course, at all points of the wind-tunnel circuit. One notable exception is at expansion joints where it is necessary to carry the pressure load through or around the joint.

It has been found necessary to provide fixed points of anchorage to the wind-tunnel circuit at least at the test section and compressor. In some cases more fixed points may be required. This requires that

expansion joints be placed at various points to prevent build-up of
thermal stresses. A typical arrangement of these joints and points of
fixity is shown in figure 21. It should be mentioned that this parti-
cular design also provides support under the conditions of earthquake
which must be considered in designs for Ames Laboratory. The problem
of sealing these expansion joints has been solved through the use of an
inflatable rubber seal which permits freedom of motion but maintains
positive sealing pressure on the surfaces at the joint.

Welded construction is typical of all NACA wind tunnels. Nozzle
and compressor sections are fabricated in sections by welding, then
machined, and finally assembled by bolting with gaskets and commercially
available compounds used to seal the joints. The balance of the circuit
is fabricated by welding in the manufacturer's shops in units of sizes
small enough to be transported easily. These units are then assembled
by welding at the site. Rigorous tolerances on dimensions to maintain
the proper air flow are generally necessary in the nozzles and compres-
sors. As an example, the coordinates of the contour in a nozzle having
an 8- by 7-foot cross section are held within 0.010 inch; but, of much
more importance, the variation in radius of curvature of the contour
from that which would have a theoretically smooth second derivative is
limited by actual measurement to an amount which will not cause flow
disturbances of more than 0.03°. Curvature gages of several different
gage lengths are used in measuring the actual wall curvature. Gage
readings are plotted and the deviations are converted by calculation
into equivalent stream deflection angles. In other portions of the
wind-tunnel circuit where dimensions are less critical, the tolerances
are relaxed accordingly. Thus, the circular connecting tubes are held
in roundness to within only 1 percent of the theoretical radius, except
at points where connections to other equipment must be made. The selec-
tion of tolerances is based on experience, and it has been found that
relaxation of tolerances in noncritical regions has no effect on the
wind-tunnel performance but may result in a substantial saving in cost.

Except for the sections of the wind-tunnel circuit having high flow
velocities, the interior surface conditions are of little importance.
Welds in the low-velocity regions are ground smooth and offsets are kept
to a minimum but no precautions beyond these are considered necessary.

Before the wind tunnel is placed in service, it is given a test to
insure its structural integrity. This can be done either hydrostatically
or aerostatically. The former type of test is not considered adequate
for design pressures below 5 atmospheres absolute because the weight of
the water causes stresses, sometimes of opposite sign, which are of the
same order of magnitude as the pressure stresses, and a true simulation
of operating conditions is not afforded. The hydrostatic test can also
cause great added expense in connection with the additional supports,
either temporary or permanent, which must be provided to support the
weight of the water. However, at pressures above 5 atmospheres absolute,
it is considered desirable because of the inherent dangers associated
with aerostatic testing at high pressures.

Test Instrumentation

The use of schlieren apparatus for study of supersonic flow fields is always desirable. Windows of optical quality glass are thus a necessity in the walls of the test section. Windows as large as 54 inches in diameter have been procured for this purpose but these are extremely expensive and difficult to control in quality. A sounder approach appears to be that of providing large cutouts in the test-section walls with provisions for mounting smaller windows opposite the points of interest with the balance of the schlieren equipment made somewhat portable to permit surveying of the entire cutout area. Another idea which has been used is that of dividing the large cutout into a number of sections, each having its own window pane. A large mirror system can then be used and the whole field, except for that obscured by the structural supports for the individual window panes, can be observed. Another possible optical system for use with supersonic wind tunnels is the interferometer, but it is currently considered impractical for large installations.

Pressure and force recording instrumentation are, of course, required but these will vary widely in form and will have very little effect on the design of the wind tunnel. However, the design of the instrumentation may be greatly affected by a requirement for rapid functioning because of the costly operation of high-powered wind tunnels. Considerable effort has been expended in the NACA Unitary facilities to provide rapid reading, recording, and computation of the data without sacrificing reliability. To accomplish this purpose, considerable use will be made of electronic recording and computing equipment. Much of this equipment is, as yet, only under development; however, systems producing correctly computed data points in plotted form at 2-minute intervals, or less, after reading, seem assured.

Concluding Remarks

The experience in design of large high-speed wind tunnels presented here represents, largely, that gained in construction of several such facilities at the Ames Laboratory. The scope of discussion has been limited by the authors to the major design problems, and undoubtedly other equally acceptable solutions to some of the problems mentioned may be readily apparent to the reader.

Our primary purpose has been to emphasize that the design of any large high-speed wind tunnel brings together unusual problems from many fields of the engineering profession. It is important that each problem be viewed with the proper perspective in order that the best balance of engineering judgment can be realized. As in other engineering work,

the final design will contain numerous compromises which must be made,
but not at the expense of sacrificing proper aerodynamic operation;
for the wind tunnel is a research tool whose aerodynamic precision must
match that of the research work for which it has been designed.

REFERENCES

1. Allen, H. Julian: The Asymmetric Adjustable Supersonic Nozzle for
   Wind Tunnel Application. NACA TN 2919, 1953.

2. Syvertson, Clarence A., and Savin, Raymond C : The Design of Variable
   Mach Number Asymmetric Nozzles by Two Procedures Employing Inclined
   and Curved Sonic Lines. NACA TN 2922, 1953.

3. Burbank, Paige B., and Byrne, Robert W.: The Aerodynamic Design and
   Calibration of an Asymmetric Variable Mach Number Nozzle with a
   Sliding Block for the Mach Number Range 1.27 to 2.75. NACA TN 2921,
   1953.

4. Tucker, Maurice: Approximate Turbulent Boundary-Layer Development
   in Plane Compressible Flow Along Thermally Insulated Surfaces with
   Application to Supersonic-Tunnel Contour Correction. NACA TN 2045,
   1950.

5. Neumann, Ernest P., and Lustwerk, F.: High Efficiency Supersonic
   Diffusers. Jour. Aero. Sci., June 1951, pp. 369-374.

6. Diggins, J. L., and Lange, A. H.: A Systematic Study of a Variable
   Area Diffuser for Supersonic Wind Tunnels. NAVORD Rep. 2421,
   Dec. 1952.

7. Eggink, Dr. H.: The Improvement in Pressure Recovery in Supersonic
   Wind Tunnels. R.A.E. Rep. No. Aero. 2326, S.D. 34, May 1949.

8. Liepmann, Hans Wolfgang, and Puckett, Allen E.: Introduction to
   Aerodynamics of a Compressible Fluid. John Wiley and Sons, Inc.,
   1947, pp. 85-86.

9. Erwin, John R., and Emery, James C.: Effect of Tunnel Configuration
   and Testing Technique on Cascade Performance. NACA TN 2028, 1950.

10. Zinney, C. M., and Lappi, V. M.: Data for Design of Entrance Vanes
    from Two-Dimensional Tests of Airfoils in Cascade. NACA ACR L5G18,
    1945.
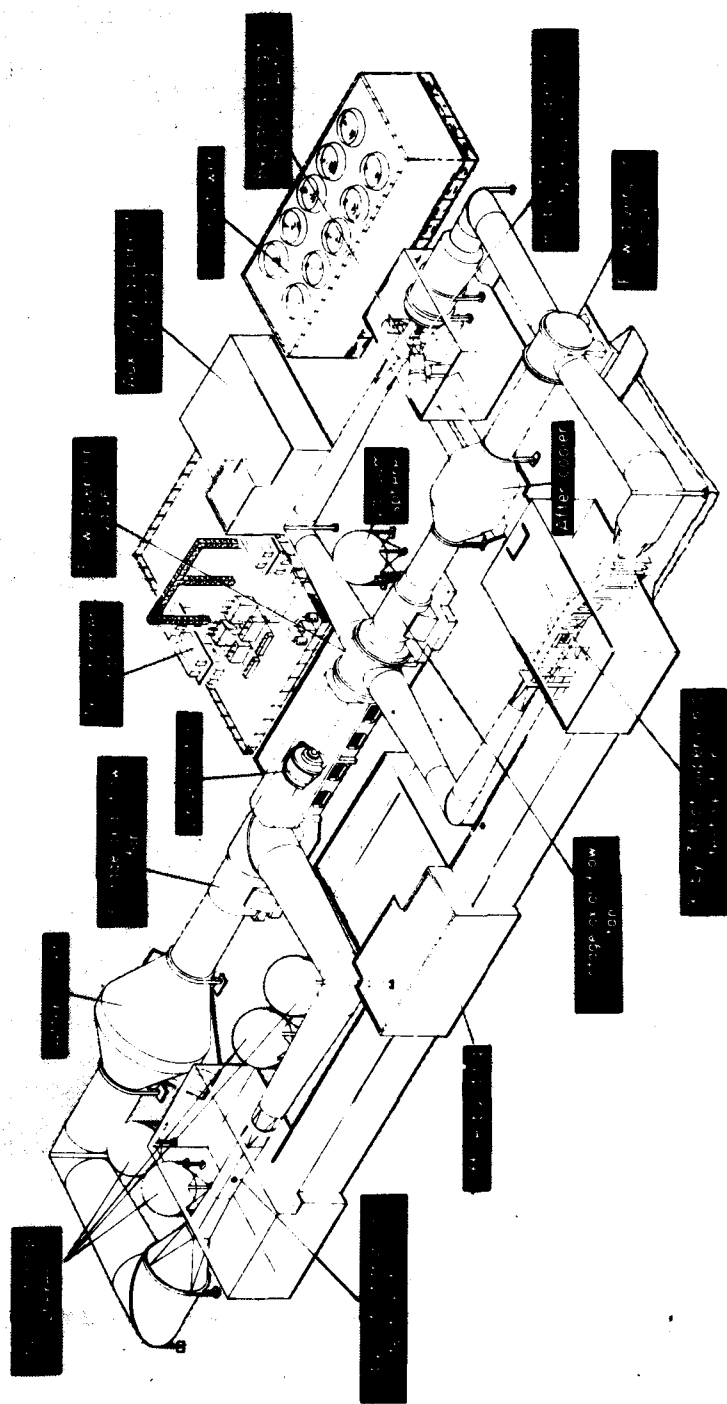
Figure 1.- General arrangement of the Unitary facility, Ames Aeronautical Laboratory.
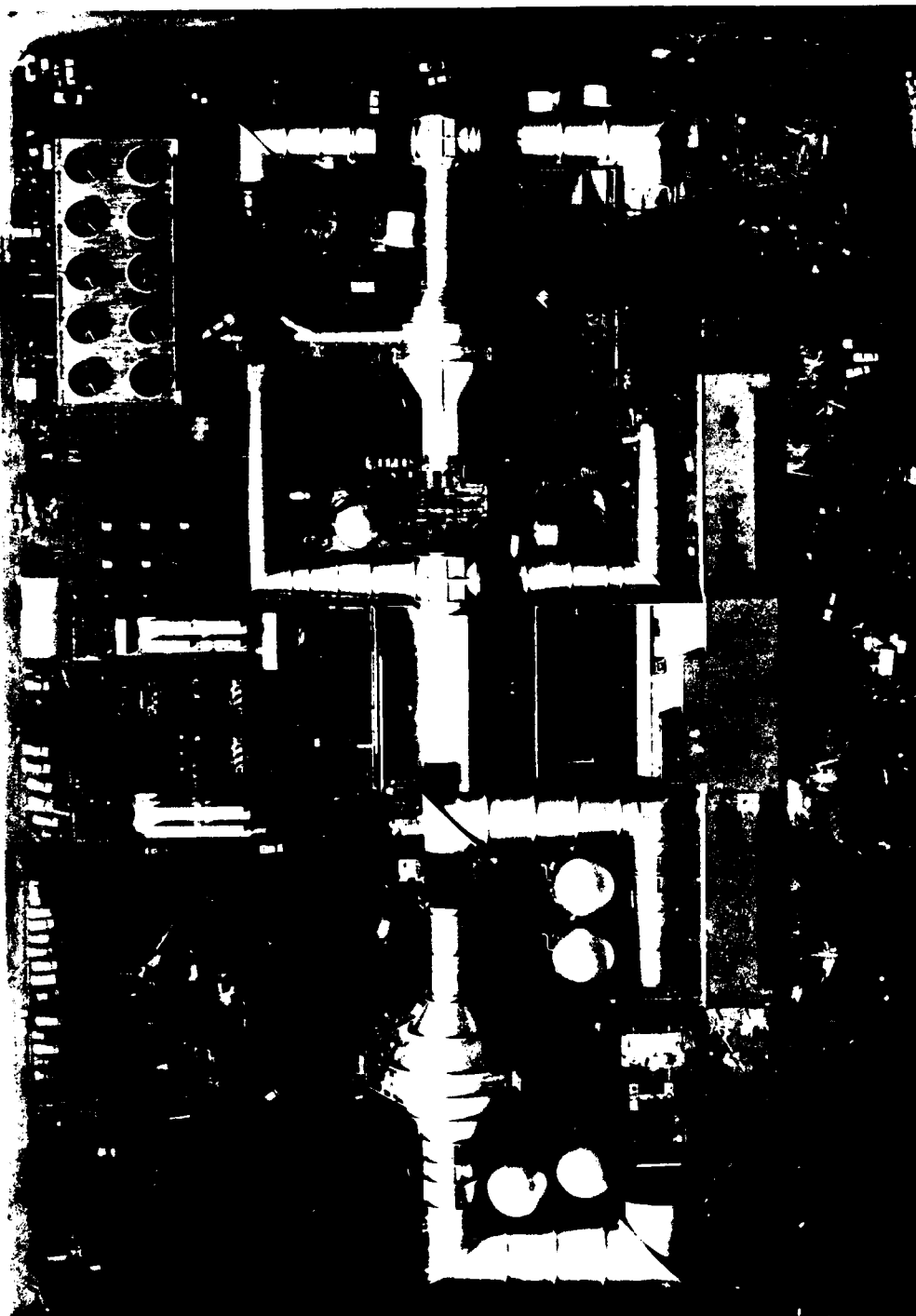
Figure 2.- Aerial view of the Unitary facility, Ames Aeronautical Laboratory.

A-8 ft. SSWT-162
3-25-54
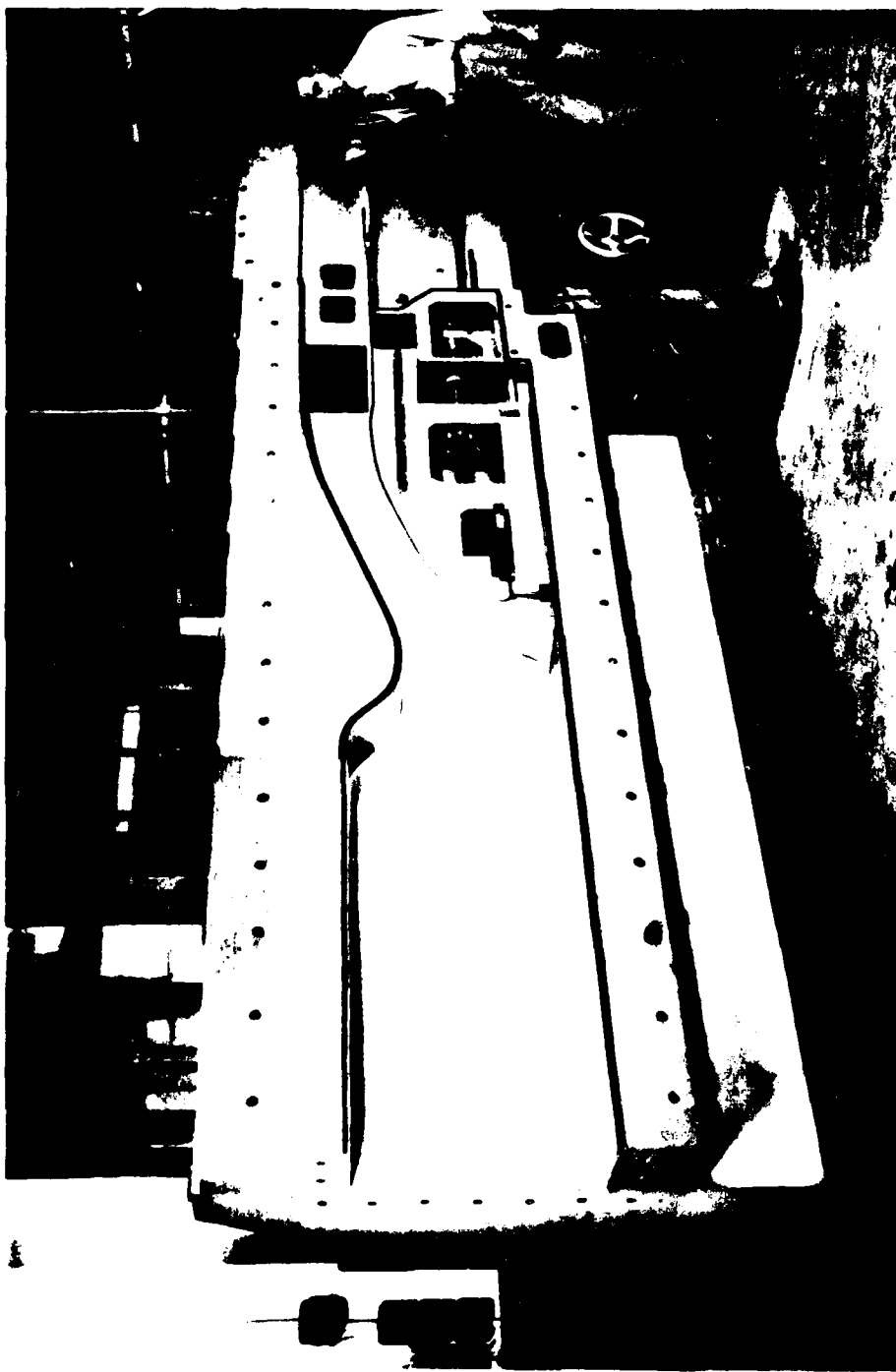
A-15462

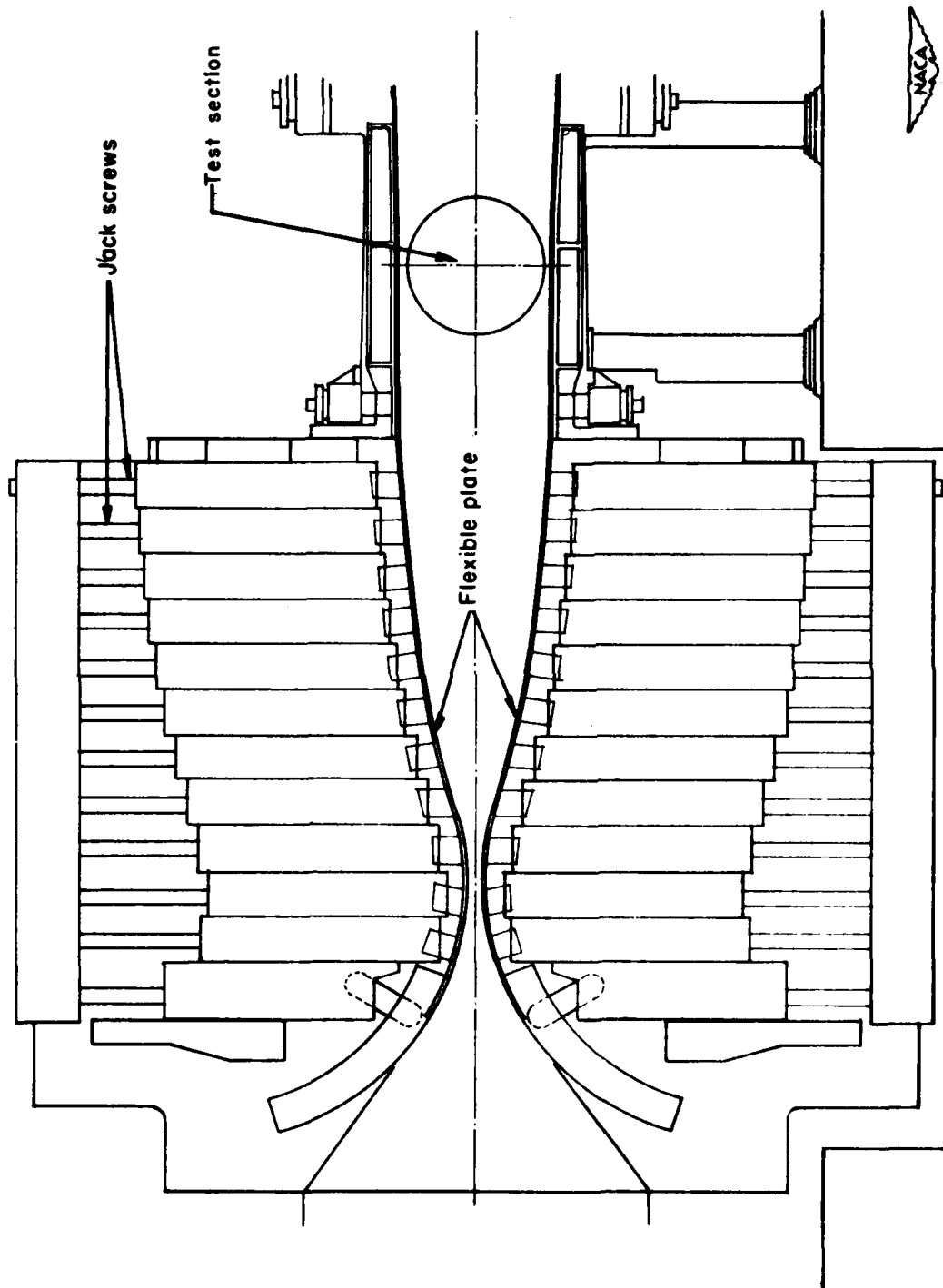Figure ... the superstructure test equipment with side wall removed.
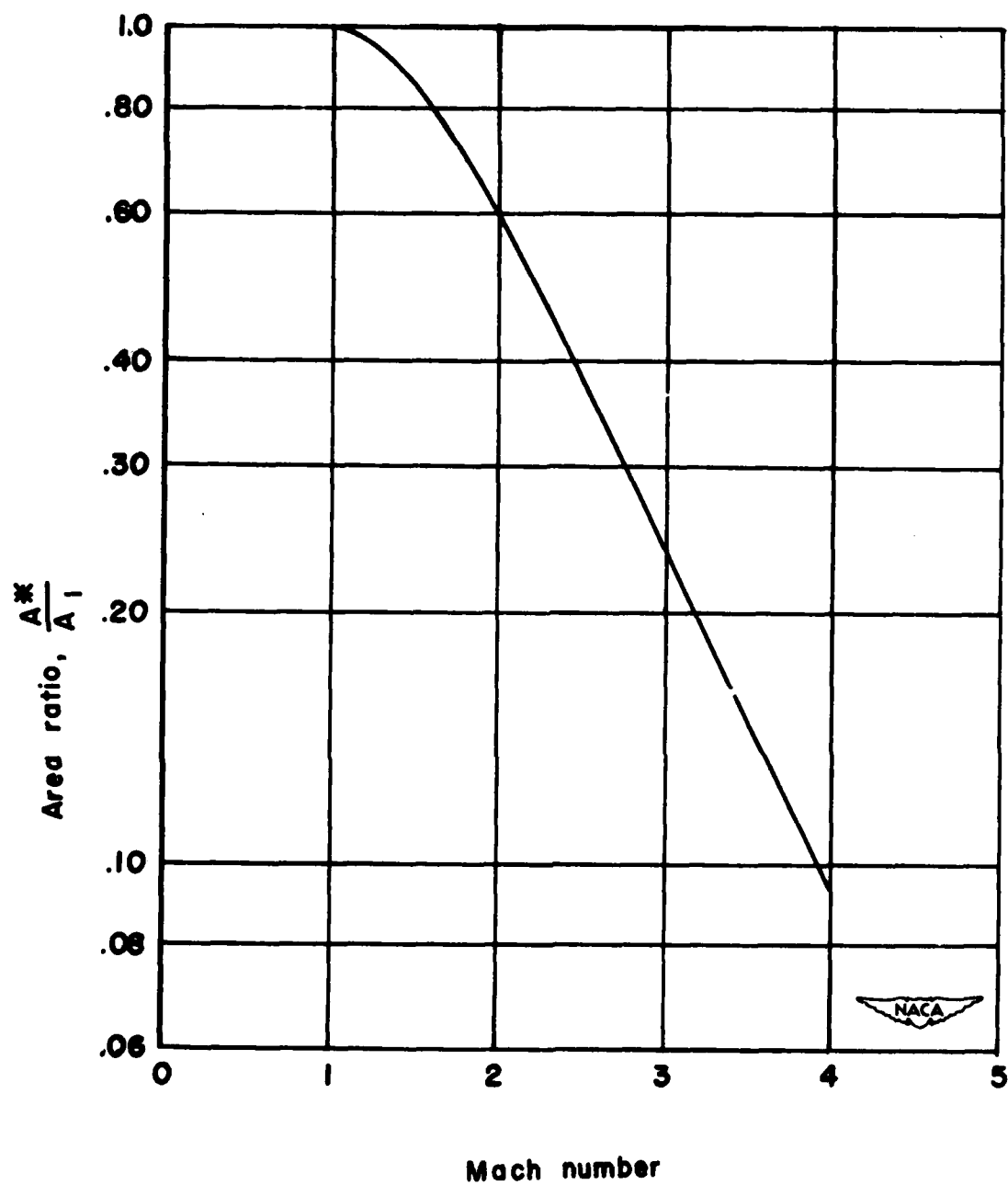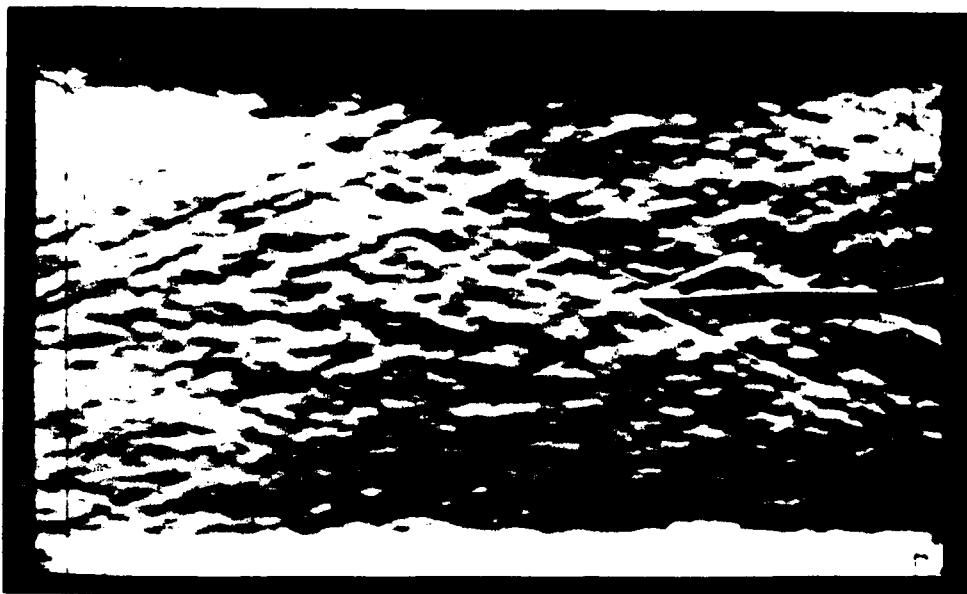
Figure 4.- Arrangement of a typical symmetric supersonic flexible-wall nozzle.

Figure 5.- Ratio of throat to test-section area for supersonic nozzles.

A-19147

(a) Original nozzle blocks.

A-19138

(b) Modified nozzle blocks.

Figure 6.- Schlieren photographs of flow in an asymmetric
supersonic nozzle.
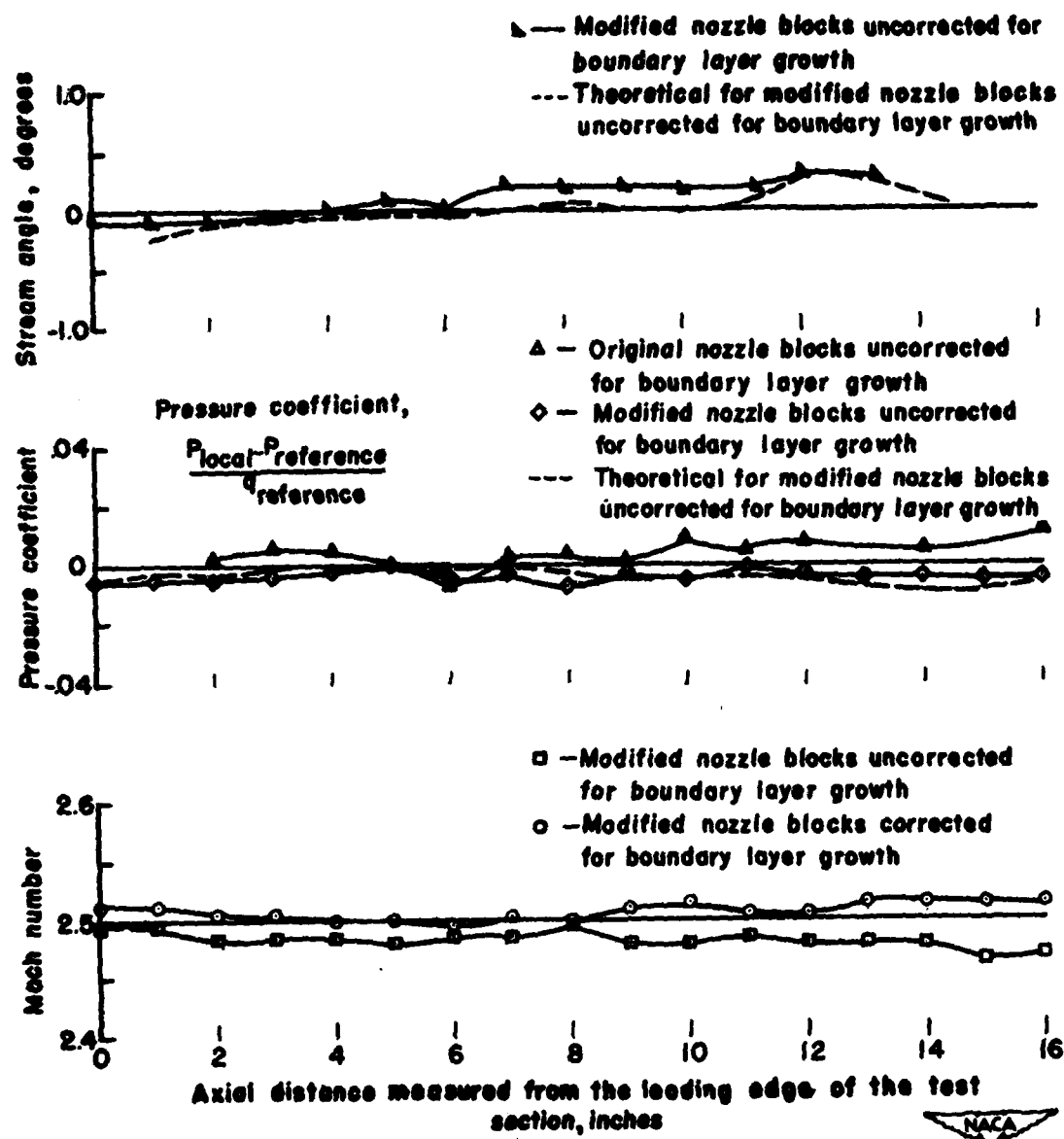
Figure 7.- Flow conditions along the center line of the test section of an asymmetric supersonic nozzle; M = 2.50.

Figure 8.- Arrangement of a flexible-wall nozzle having a fixed portion in the region of the throat.

Hinges

Solid block

Thrust cylinders

Support frame

Hydraulic motors

Jack screws

Gear reducers

Pressure shell

Flexible plate

Trunnions

Rocker joints

Test section

NACA
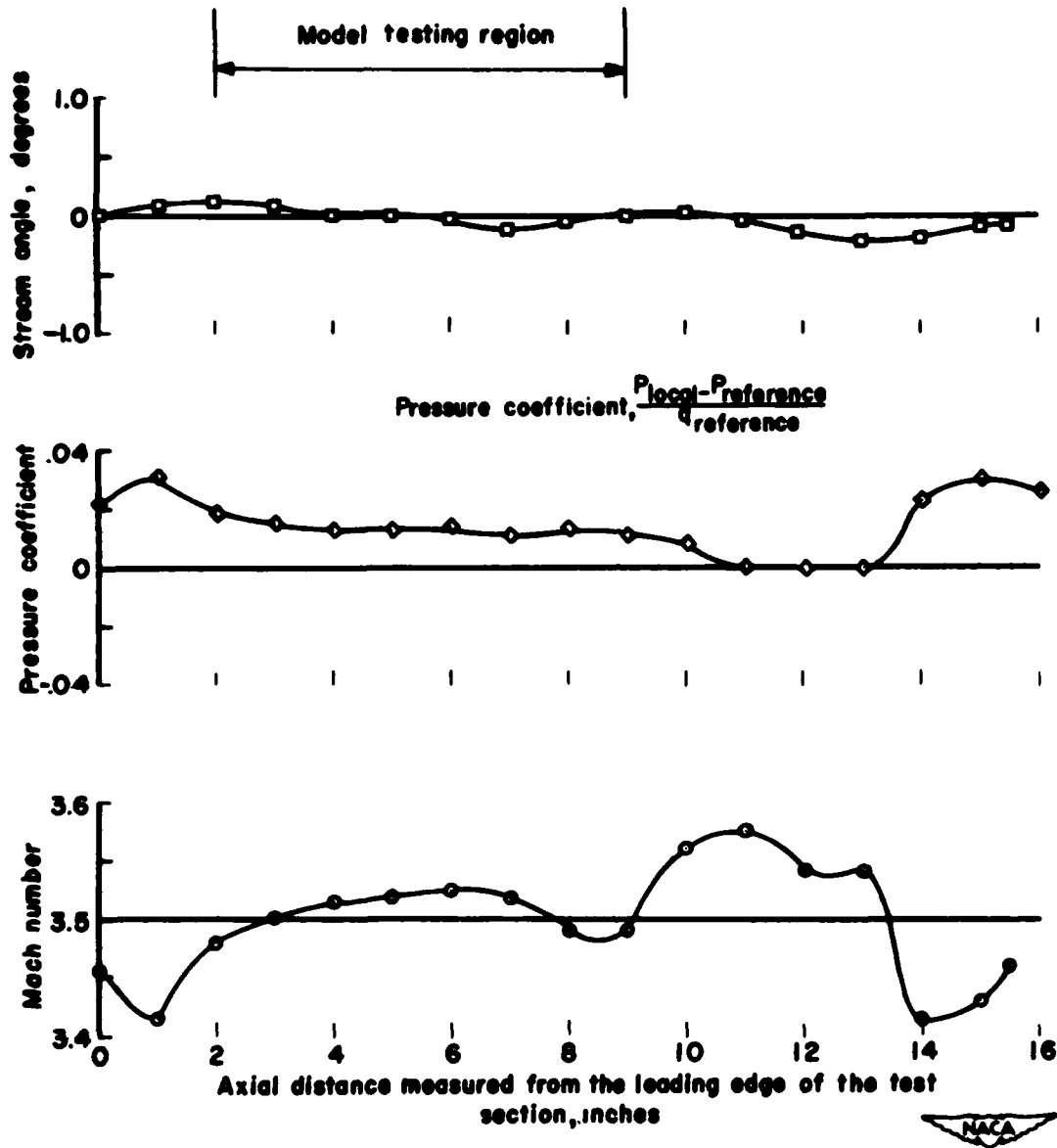
Figure 9.- Flow conditions along the center line of the test section of a symmetric supersonic nozzle; M = 3.50.
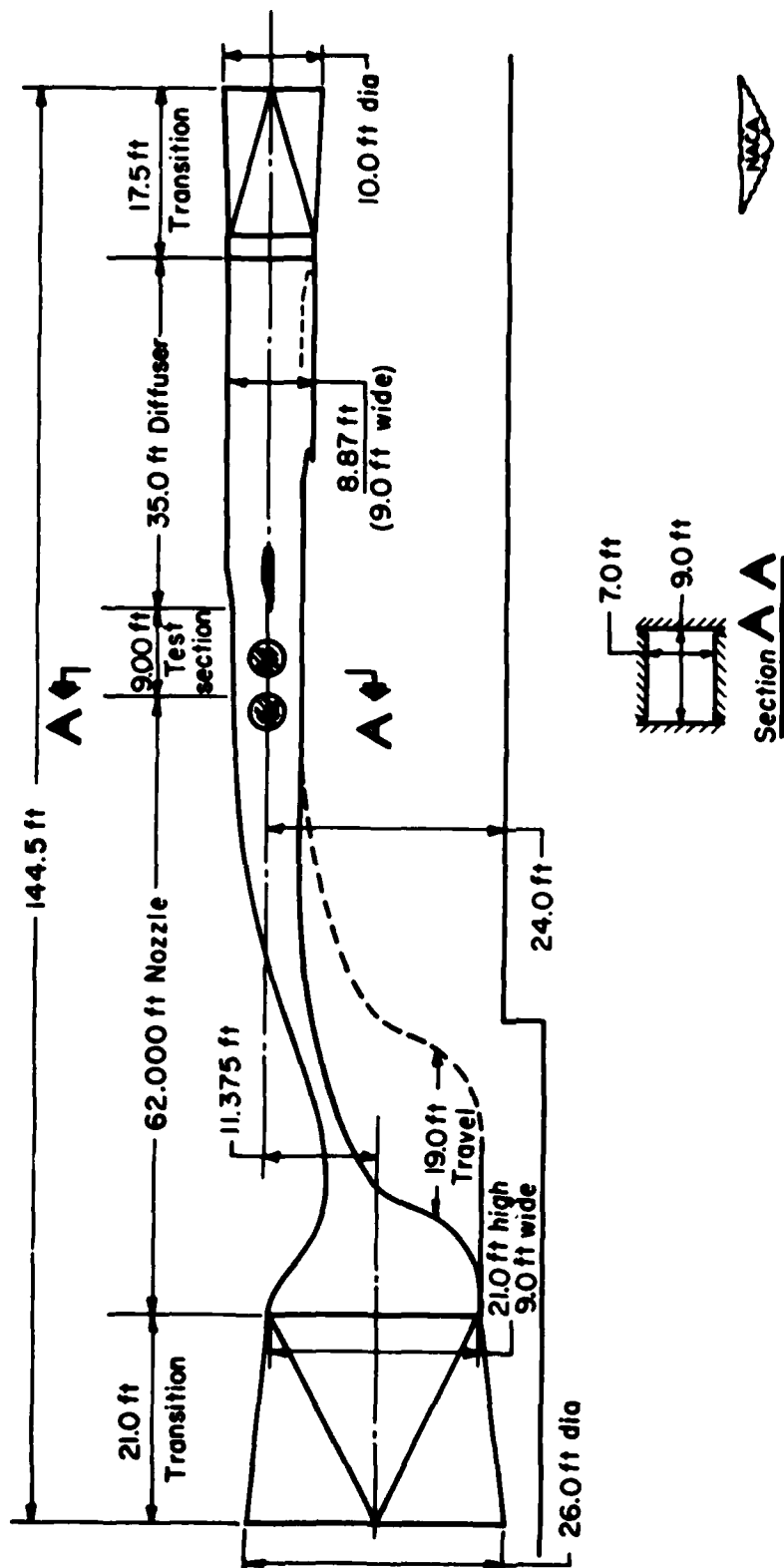
Figure 10.- Arrangement of asymmetric nozzle of Ames Unitary facility.
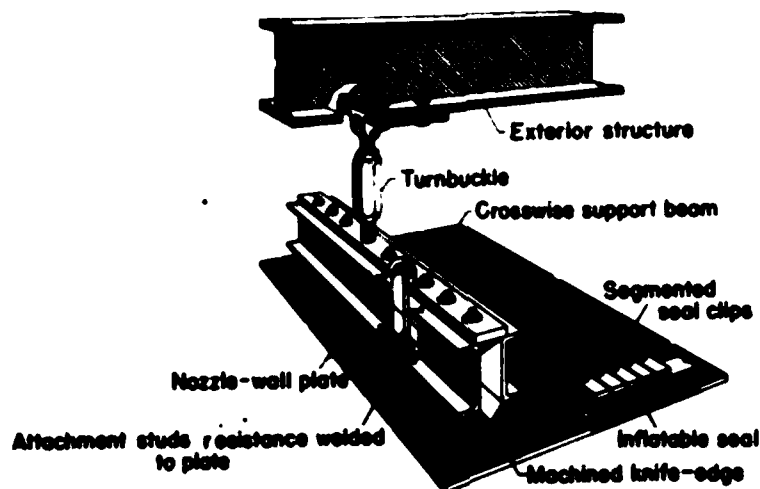
(a) Nozzle-wall supporting structure for asymmetric
nozzle.
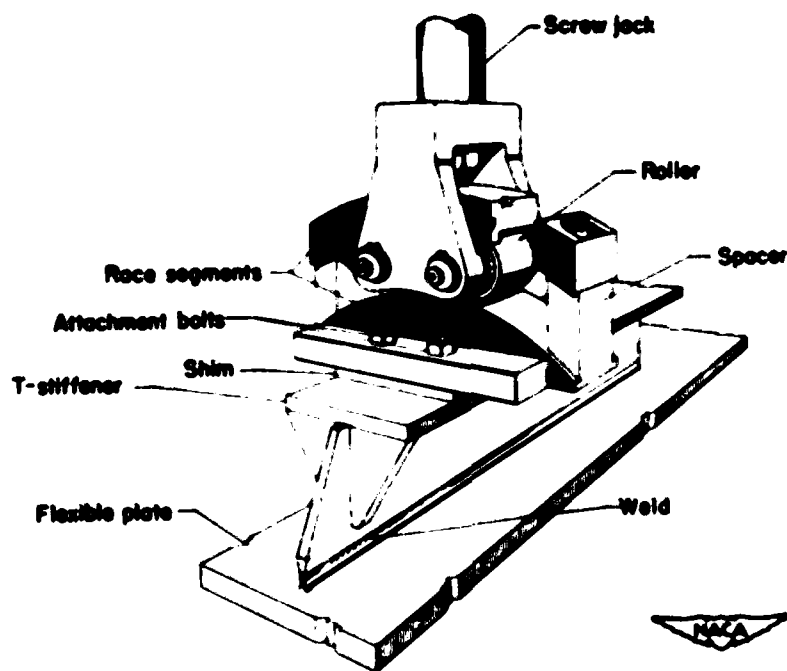
(b) Rocker-joint attachment of jackscrews to flexible
plate.

Figure 11.- Methods of supporting flexible plates for supersonic
nozzles used in Ames Unitary facility.
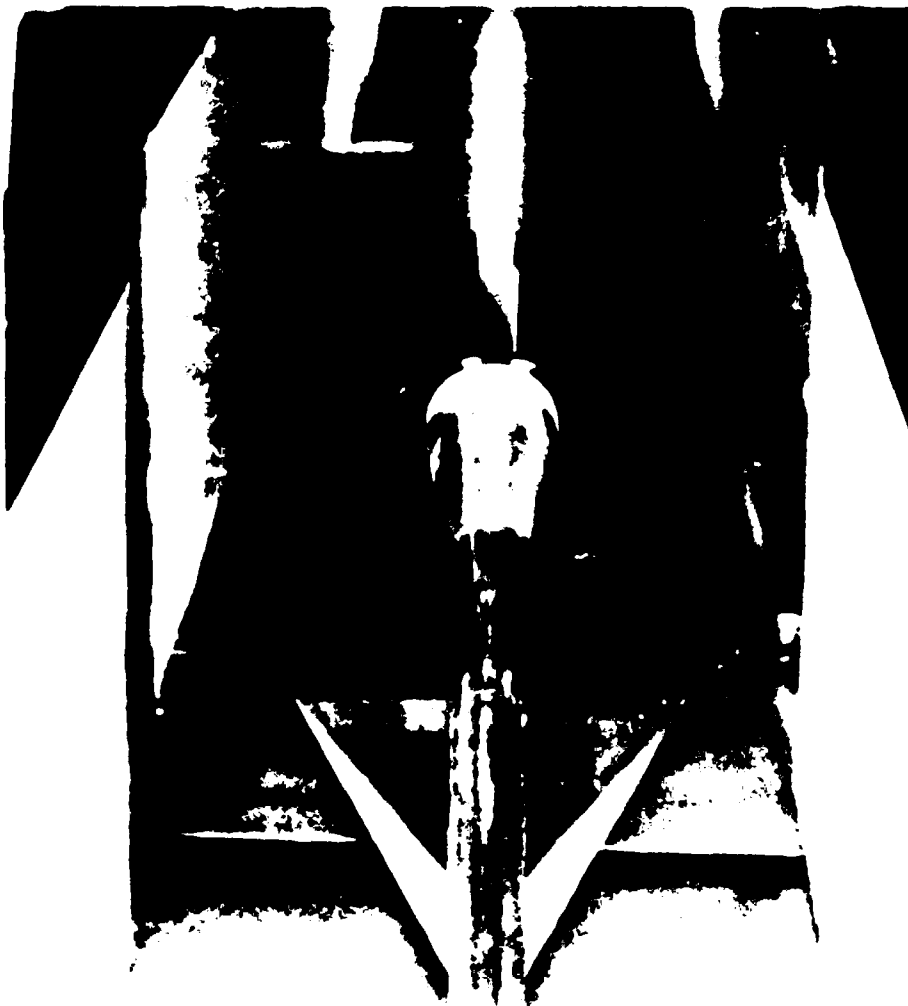
Figure 1. - Typical sting-supported model in a supersonic wind tunnel.

A-18208.1
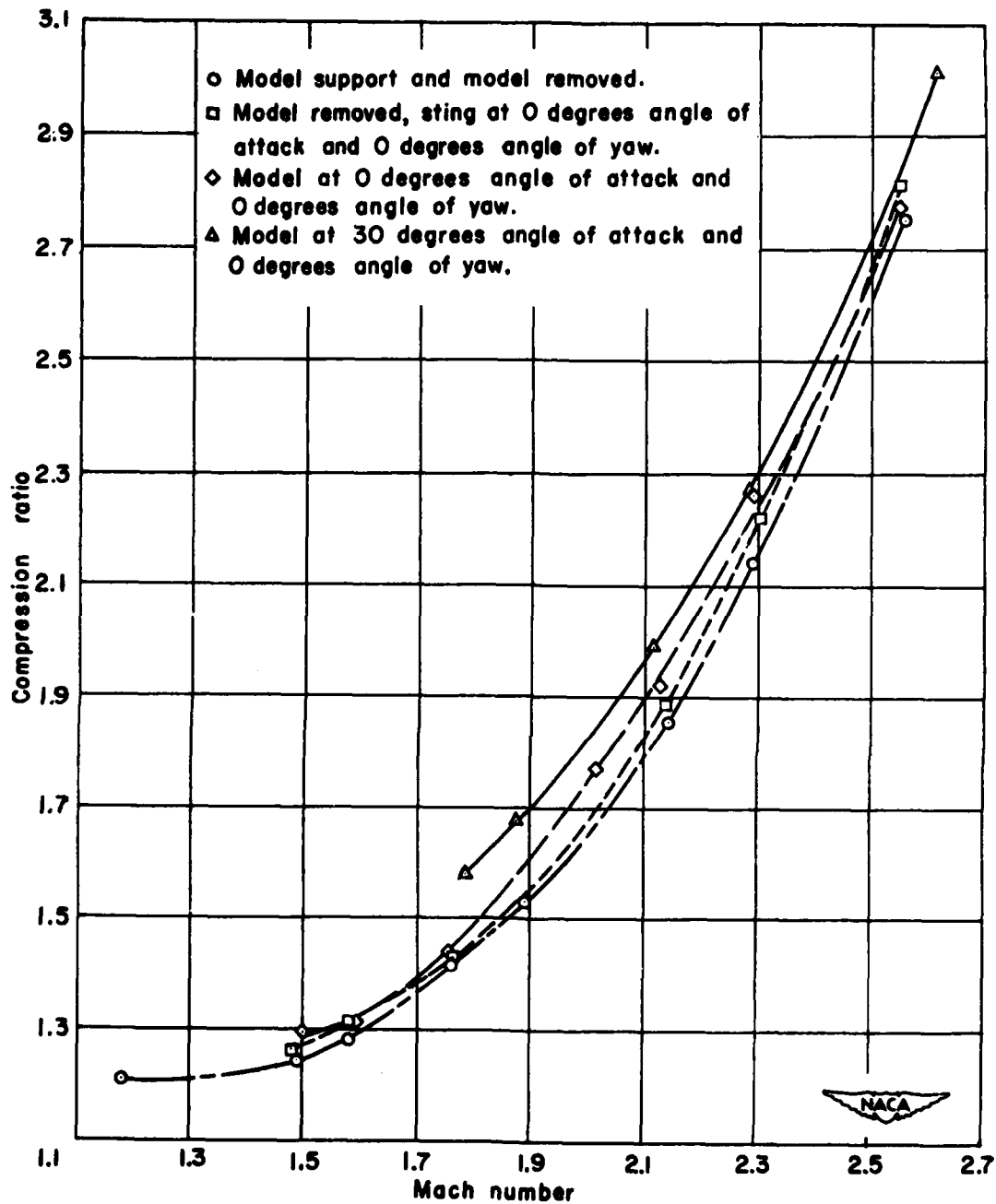
Figure 13.- Variation of minimum running compression ratio with Mach
number for the 8-inch supersonic nozzle test equipment with
asymmetric nozzle blocks, model support, and diffuser.

Q/R for compressor

$\dfrac{Q}{R}$

Tunnel characteristic showing
effect on Q/R of altering test
section area or stagnation
temperature.

$\dfrac{Q}{R}$

B

C   C'

Compression ratio, R

R

Constant M   Design Point

Efficiency
contour

Surge

A

Typical
compressor
characteristics
at several
speeds.

D   D'

Typical wind tunnel
characteristic curves
for several diffuser
efficiencies.

Flow quantity, Q

Mach Number, M

Figure 14.- Relationship between wind tunnel and compressor
characteristics.
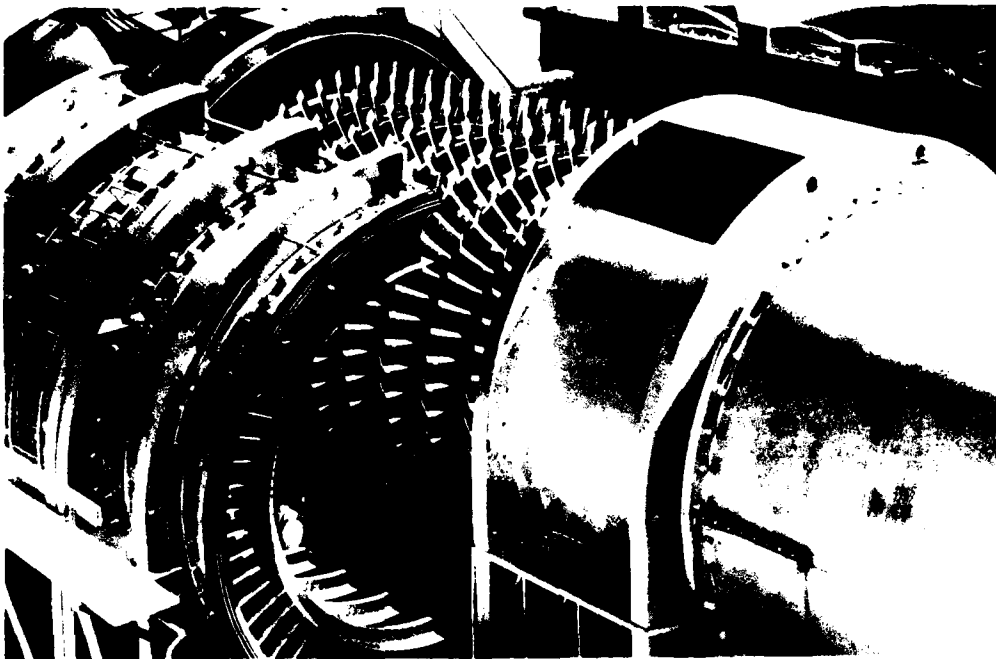
(a) Compressor of the transonic aerodynamic wind tunnel. At the
Aerodynamics Institute, Laboratory.

(b) Compressor of the transonic aerodynamic propulsion wind tunnel,
with high-speed stage compressor.

Figure ... The axial ... ... the NASA wind ...
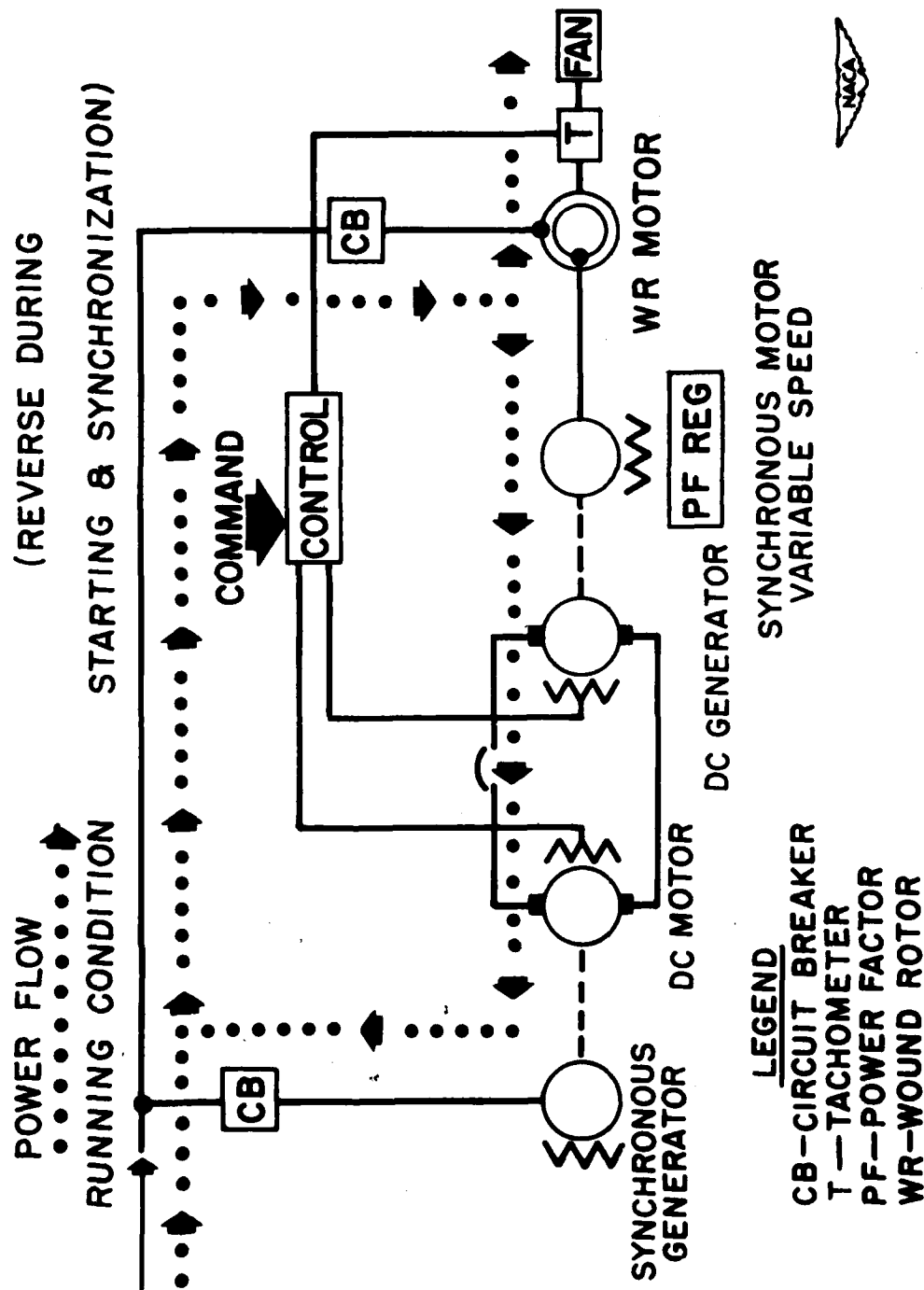
Figure 16.- Schematic diagram of modified Kramer variable-speed electrical power system.

COMPRESSOR

LEGEND
CB — CIRCUIT BREAKER

CONTROL - COMMAND

CB

CB

PILOT
MOTOR

WOUND ROTOR
MOTORS

LIQUID RHEOSTAT
SLIP REGULATOR
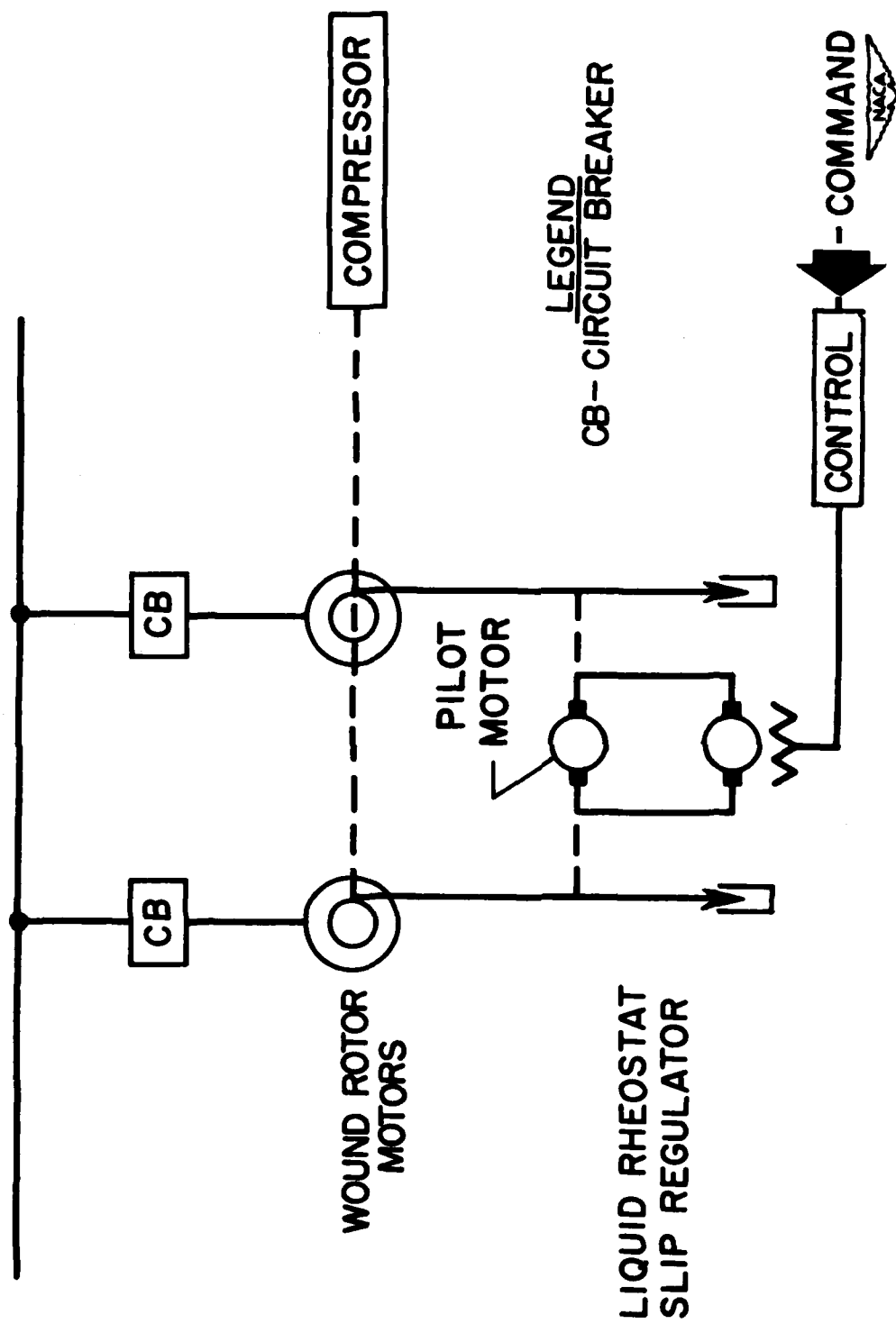
Figure 17.- Schematic diagram of simple slip regulator variable-speed electrical power system for a pair of motors.
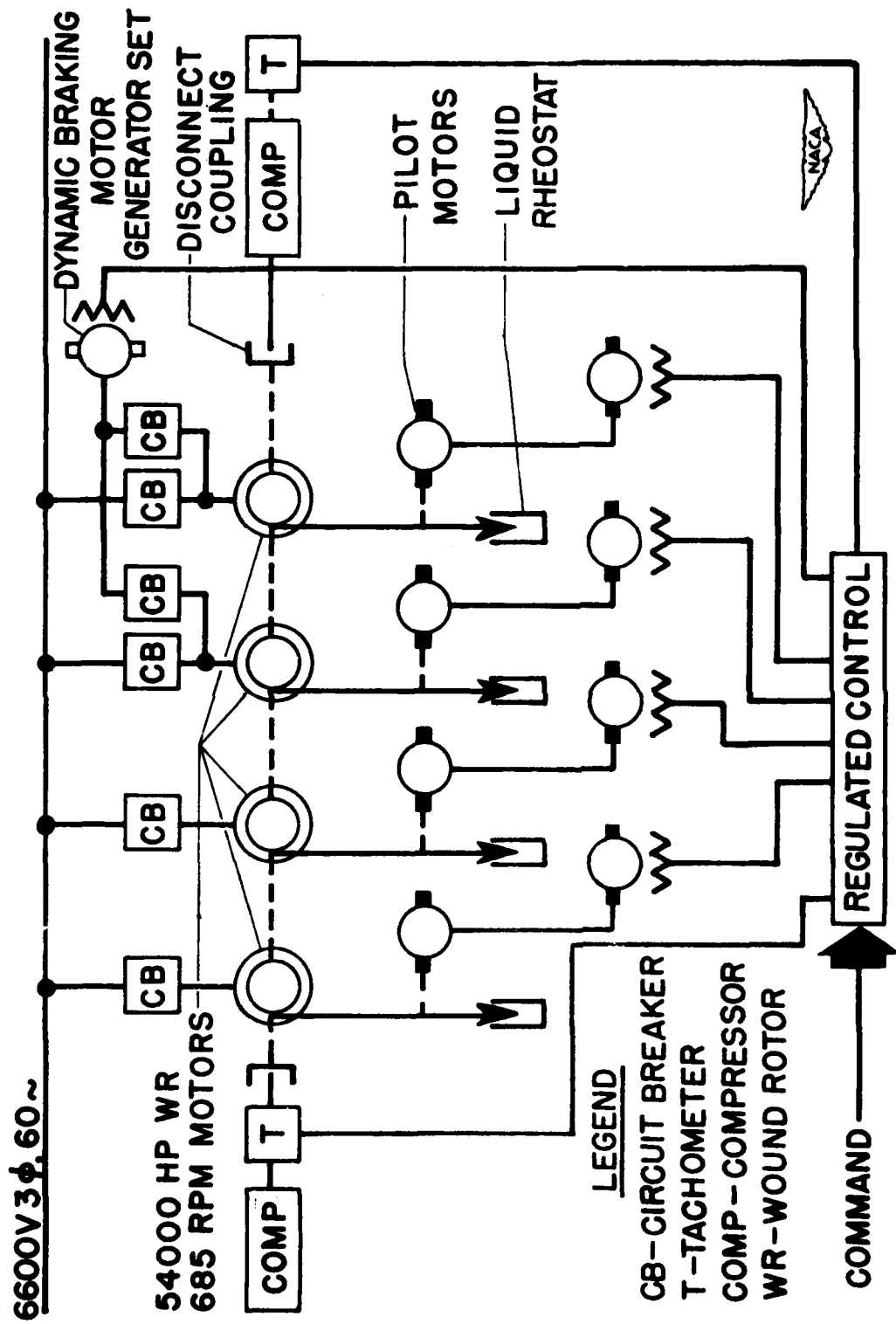
Figure 18.- Schematic diagram of the variable-speed electrical power system of the Unitary facility, Ames Aeronautical Laboratory.
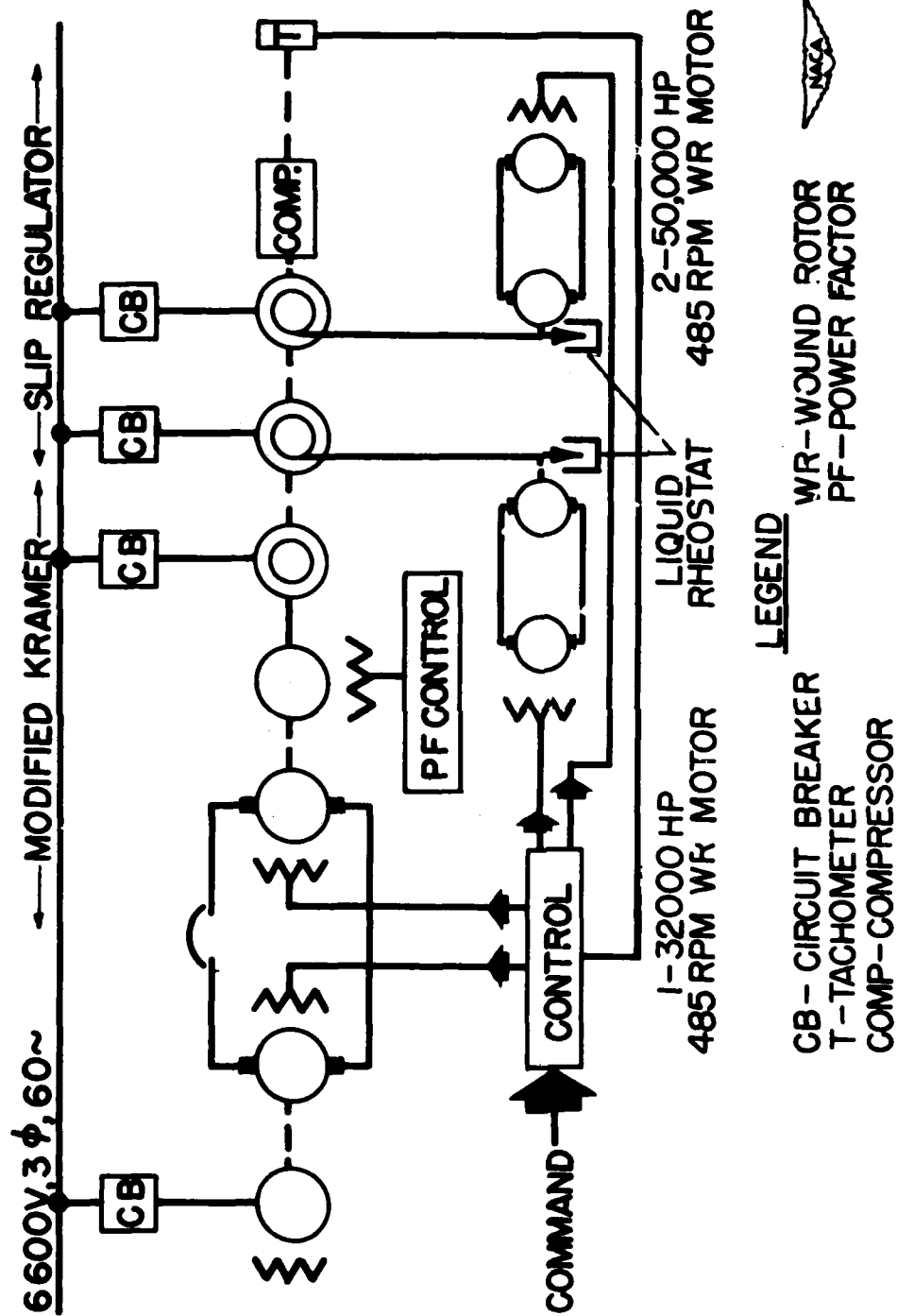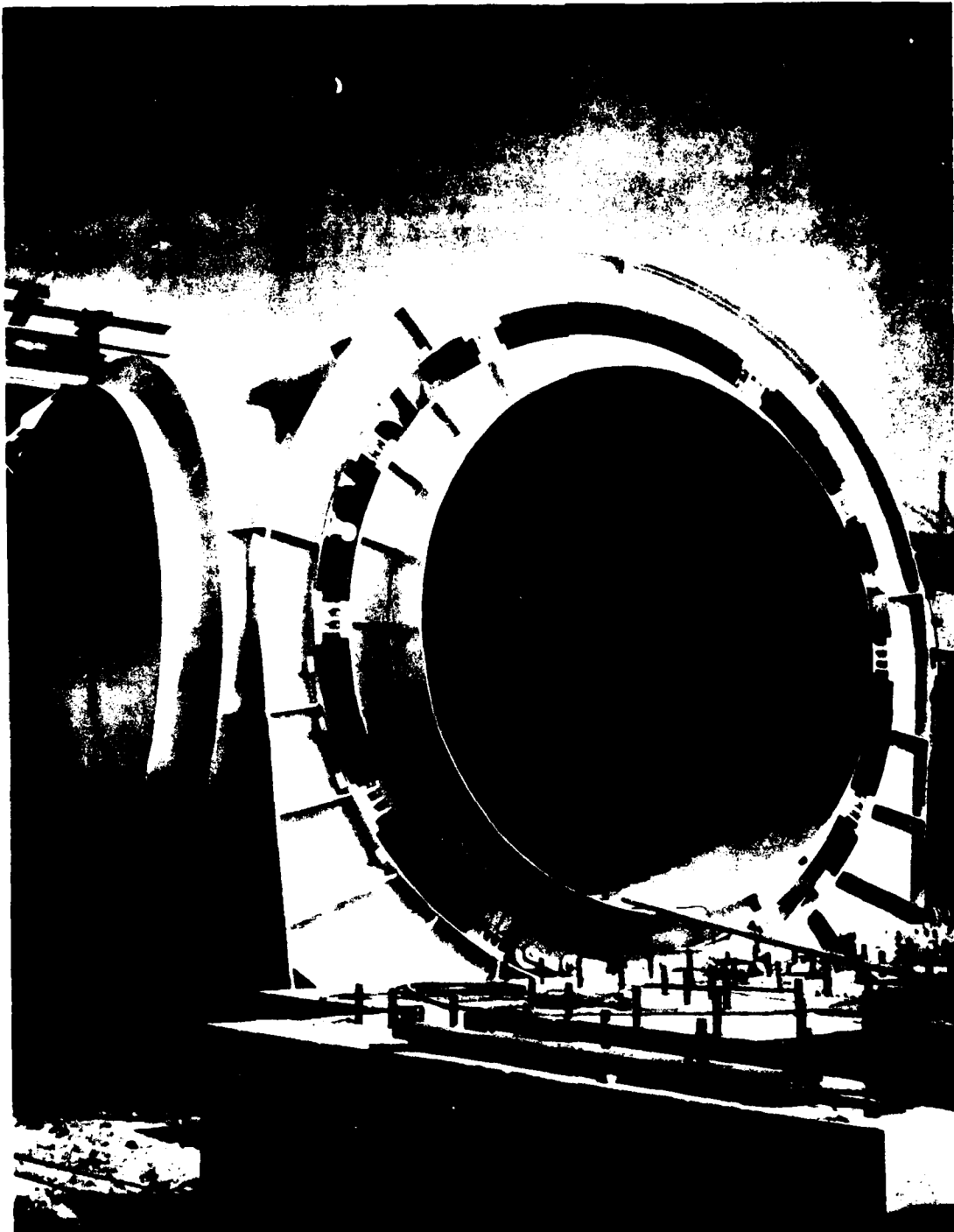
Figure 19.- Schematic diagram of variable-speed electrical power system of the 16-foot transonic wind tunnel, Ames Aeronautical Laboratory.

A-8 ft. SSWT-120
9-4-53

Figure ... - Transverse Section ... Mach 1 ... Pressure Facility,
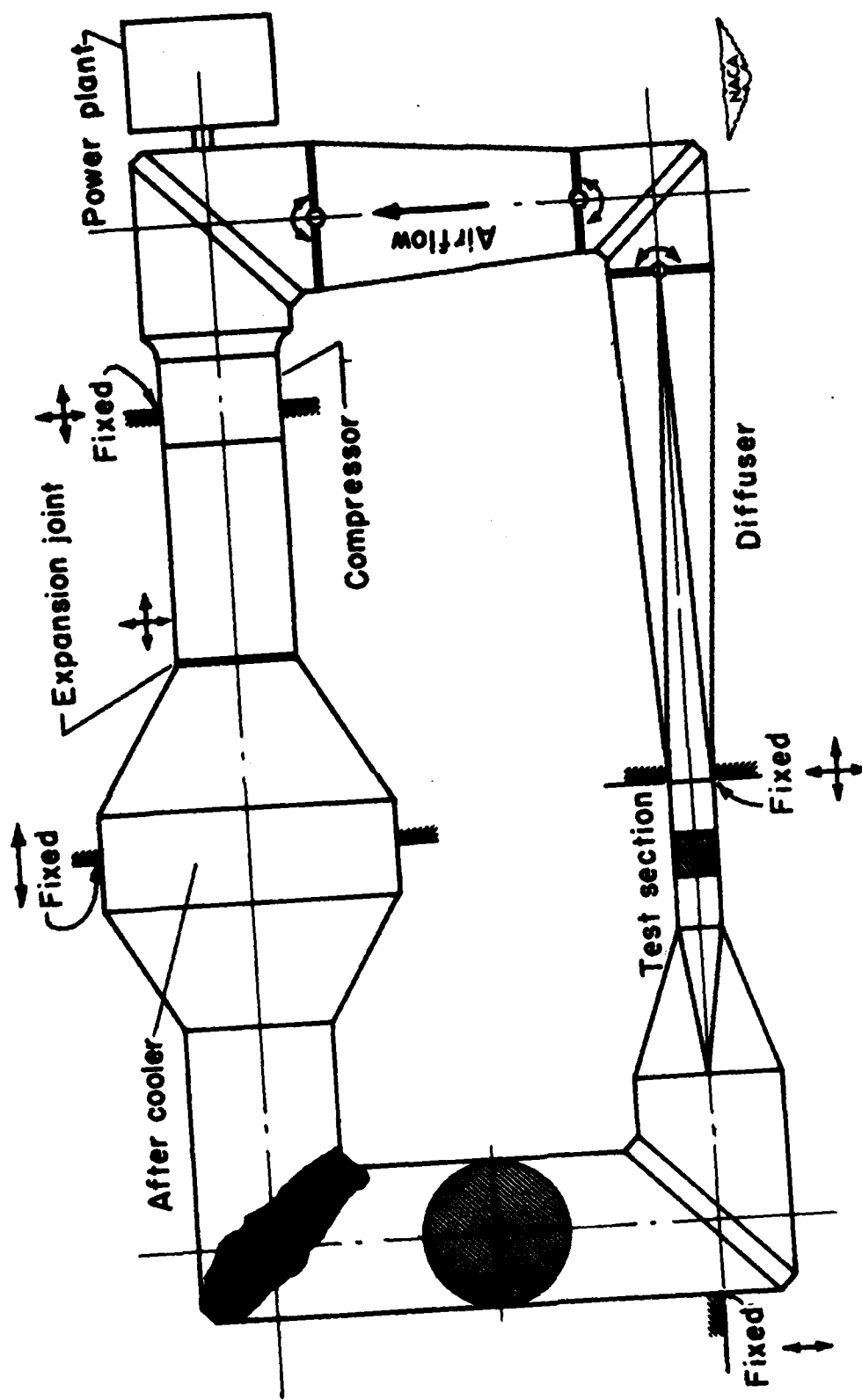Arc... Aerodynamics Laboratory.

Figure 21.- Typical arrangement of fixed points and expansion joints in a variable-density supersonic wind tunnel.